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## A System Dynamics Model For Manpower And Technology Implementation Trade-off And Cost Estimation

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# A SYSTEM DYNAMICS MODEL FOR MANPOWER AND TECHNOLOGY IMPLEMENTATION TRADE-OFF AND COST ESTIMATION

by

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A dissertation submitted in partial fulfillment of the requirements  
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in the Department of Industrial Engineering and Management Systems  
in the College of Engineering and Computer Science  
at the University of Central Florida  
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## **ABSTRACT**

The U.S. Navy has been confronted with budget cuts and constraints during recent years. This reduction in budget compels the U.S. Navy to limit the number of manpower and personnel to control costs. Reducing the total ownership cost (TOC) has become a major topic of interest for the Navy as plans are made for current and future fleets. According to the U.S. Government Accountability Office (GAO, 2003), manpower is the most influential component of determining the life cycle cost of a ship. The vast majority of the TOC is comprised of operating and support (O&S) costs which account for approximately 65 percent of the TOC. Manpower and personnel costs account for approximately 50 percent of O&S costs.

This research focused on tradeoff analysis and cost estimation between manpower and new technology implementation. Utilizing concepts from System Dynamics Modeling (SDM), System Dynamics Causal Loop diagrams (CLD) were built to identify major factors when implementing new technology, and then stocks and flows diagrams were developed to estimate manpower cost associated with new technology implementation. The SDM base model reflected an 18 months period for technology implementation, and then compared different technology implementation for different scenarios. This model had been tested by the public data from Department of the Navy (DoN) Budget estimates.

The objective of this research was to develop a SDM to estimate manpower cost and technology tradeoff analysis associated with different technology implementations. This research will assist Navy decision makers and program managers when objectively considering the impacts of

technology selection on manpower and associated TOC, and will provide managers with a better understanding of hidden costs associated with new technology adoption.

Recommendations were made for future study in manpower cost estimation of ship systems. In future studies, one particular type of data should be located to test the model for a specific manpower configuration.

## KEYWORDS

Total ownership cost (TOC), Manpower Cost Estimation, Manpower requirement, Manpower technology trade-off, System Dynamics Modeling (SMD).

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## **CHAPTER ONE: INTRODUCTION**

### **1.1 Background**

The U.S. Navy has been confronted with budget cuts and constraints during recent years. This reduction in budget compels the U.S. Navy to limit the number of manpower and personnel. Reducing the total ownership cost (TOC) has become a major topic of interest for the Navy as plans are made for current and future fleets. According to the U.S. Government Accountability Office (GAO, 2003), manpower is the most influential component of determining the life cycle cost of a ship. The vast majority of the TOC is comprised of operating and support (O&S) costs which account for approximately 65 percent of the TOC. Manpower and personnel costs account for approximately 50 percent of O&S costs.

The Government Accountability Office (GAO) claims that “the cost of the ship’s crew is the largest expense incurred over the ship’s lifetime” (GAO, 2003). Because of this reason, the Navy has made a lot of efforts to reduce crew size on board. The future ship classes will be operated by significantly smaller crew. New technologies are being introduced into the United States military system in order to empower enhanced performance with fewer personnel.

Figure 1 depicts a historical breakdown of the life cycle cost (LCC) for a typical major weapon system. System TOC equates with LCC which includes research and development cost, investment cost, operation and support cost and disposal cost (Gilmore & Valaika, 1992). Operation and support cost accounts for approximately 60 percent of LCC.

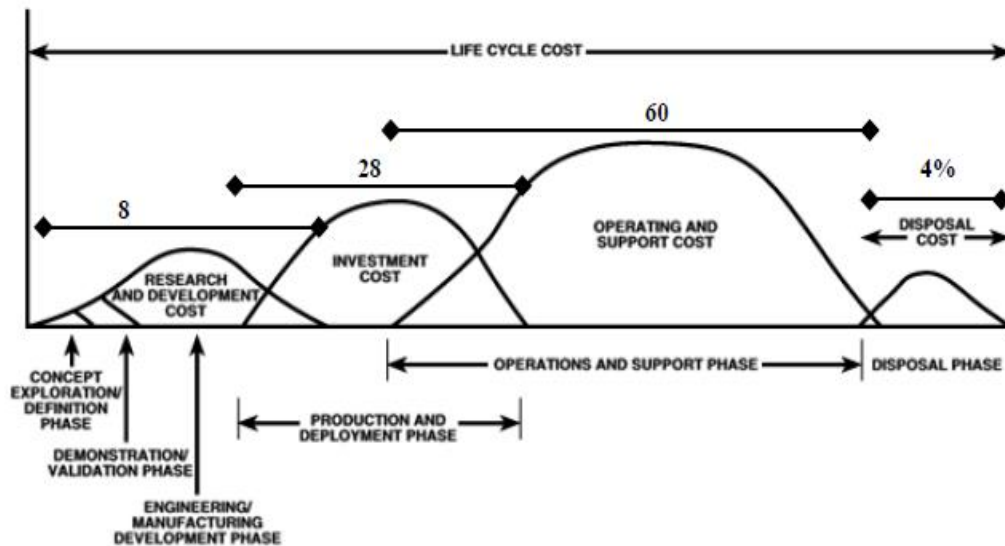


Figure 1: Life Cycle Breakdown (adapted from “Operating and Support Cost-Estimating Guide,”  
by Gilmore & Valaika, 1992)

According to Gilmore & Valaika (1992), these four phases in LCC can be described as follows:

Phase 1 Research and Development (R&D): R&D includes development and design costs for system engineering and design, test and evaluation, and other costs for system design features. It also includes costs for development, design, startup, initial vehicles, software, test and evaluation.

Phase 2 Procurement and Investment (P&I): P&I include total production and deployment costs of the system and its related support equipment and facilities. It also includes any related equipment and material furnished by the government, initial spare and repair parts, interim contractor support, and other efforts.

Phase 3 Operation and Support (O&S): O&S include those costs associated with using manpower, fuel, maintenance, and support through the entire life cycle.

Phase 4 Disposal: It includes the costs of disposing the equipment after its useful lifecycle.

Currently, the increasing sophistication of weapon systems and new technologies has increased requirements for Navy manpower. New technologies also require the Navy to coordinate manpower and technology decisions. It is critical for the Navy to determine its manpower needs for a ship readiness. Too few crews or too many members are not good ideas for optimizing source allocation (Moore et al., 2002). In order to achieve desired system performance within approved cost and other constraints, the Navy has applied Human System Integration (HSI) and advanced technologies within the total ship systems engineering process, such as DDG-51 reduced manning study (Bost and Galdorisi, 2004). The pressure to reduce manpower on Navy ships in order to reduce the ship's TOC has become a major topic for the Navy for more than a decade (Carreno et al., 2010).

According to the Department of the Army (2001), manpower includes the number of personnel of operating, maintaining, supporting and training for a system. Manpower requirements have a significant impact on system performance, such as system reliability and system maintainability (Clarke, 1990). System reliability and system maintainability have impacts on manpower in terms of number of personnel and skill levels. For example, reliability of a system determines the number of corrective maintenance actions, so does numbers and skills of maintenance personnel.

Manpower requirements are a key factor for determining manpower cost. Fully understanding manpower requirements and other cost drivers enable program managers and decision makers to make the right choice for future weapon systems launchings. It also enables the Department of Defense (DoD) to improve cost estimation and improve resource allocation. To become more efficient, the U. S. Navy must fully understand TOC cost drivers for ship systems. However, currently the U. S. Navy has not totally understood all the major TOC cost drivers.

### 1.2 Research Question

Based on the current issues and problems, my research questions are:

1. How can we help the program managers fully understand major TOC cost drivers?
2. How can we help decision makers fully understand manpower cost drivers associated with new technology implementation by using SDM approach?

### 1.3 Research Objectives

The objectives of this research are:

- 1) To identify major factors that impact Navy manpower cost associated with different technology implementation periods.
- 2) To develop a SDM to estimate manpower cost and conduct a technology tradeoff analysis.

- 3) To assist decision makers and program managers when considering the impacts of technology selection on manpower cost.
- 4) To provide managers with a better understanding of the hidden costs associated with new technology adoption.

This research focuses on tradeoff analysis and cost estimation between manpower and technology implementation in the phase of O&S. Utilizing concepts from SDM, system dynamics causal loop diagrams (CLD) were built to identify major factors when implementing new technology, and then stocks and flows diagrams were built to estimate manpower cost associated with new technology implementation. The system dynamics base model reflects an 18 month period for technology implementation, and then the result was compared with different technology implementation periods for different scenarios.

Introducing state-of-the-art technology, such as Multi-Model Watchstation (MMWS), has potential effects on required skill levels, training requirements and system performance capability. For example, additional training is needed to improve manpower skill levels due to the complexity of state-of-the-art technology. The additional training requirements increase sailors' skill levels as well as manpower cost. As a consequence, TOC increases due to the increased manpower cost after introducing this new technology.

In order to accomplish this research, articles and journal papers were reviewed to gain a broad understanding of the complex issues involving manpower cost reduction and manpower technology trade-offs. Using Human System Integration (HSI) concepts, critical variables such as manpower and manpower-technology trade-off were involved in this research. By comparing

the tradeoff results, this study sought to assist program managers when considering the impacts of technology selection on manpower cost.

#### 1.4 Expected Research Results

Expected research results are as follows:

- Identify the major factors which impact Navy manpower cost associated with new technology implementation
- Build a SDM for facilitating Navy manpower cost and training cost
- Provide information to investigate manpower cost and conduct a technology trade-off analysis so that decision makers and program managers can make better decisions
- Examine training cost for different training technologies and changing numbers of instructors

#### 1.5 Organization of this research

This research has been organized into seven chapters as follows:

- Chapter One contains the introduction of this research
- Chapter Two and Three contain literature reviews which include manpower cost and system dynamics applications in manpower related research
- Chapter Four contains the research methodology
- Chapter Five contains the modeling development details
- Chapter Six contains the discussion of research results

- Chapter Seven contains a conclusion and future study areas



## **CHAPTER TWO: MANPOWER COST METHODS REVIEW**

### **2.1 Introduction**

Since the U.S. Navy has been confronted budget cuts and constraints during recent years, it is critical for the Navy to do workforce/manpower planning in the early stages of projects. Decision makers need to consider and forecast human related factors for different purposes in order to decrease manpower cost. According to Scofield (2006), the cost of a ship crew is the largest expense for any ship system.

The following figure depicts the Department of the Navy (DoN) budget from 1998 to 2012. The yellow bars represent the amount of the Budget Authority. The Budget number was 180.32 billion in 2010. However, it dropped to 175.79 billion in 2011 and continually dropped to 161.10 billion in 2012. That is an approximately 8.4 percent reduction between the FY 2011 and FY2012. Currently the Navy is forecasting additional reductions for the FY 2013 which could be severely affected by sequestration for the FY 2014 budget.

As mentioned in Chapter One, manpower cost is the most influential component of determining the life cycle cost of a ship. Therefore, the Navy must strive to effectively reduce the costs associated with manpower in order to compensate for a decreasing budget. According to the international council on system engineering (INCOSE, 2007), human related costs usually account for approximately 67% of TOC.

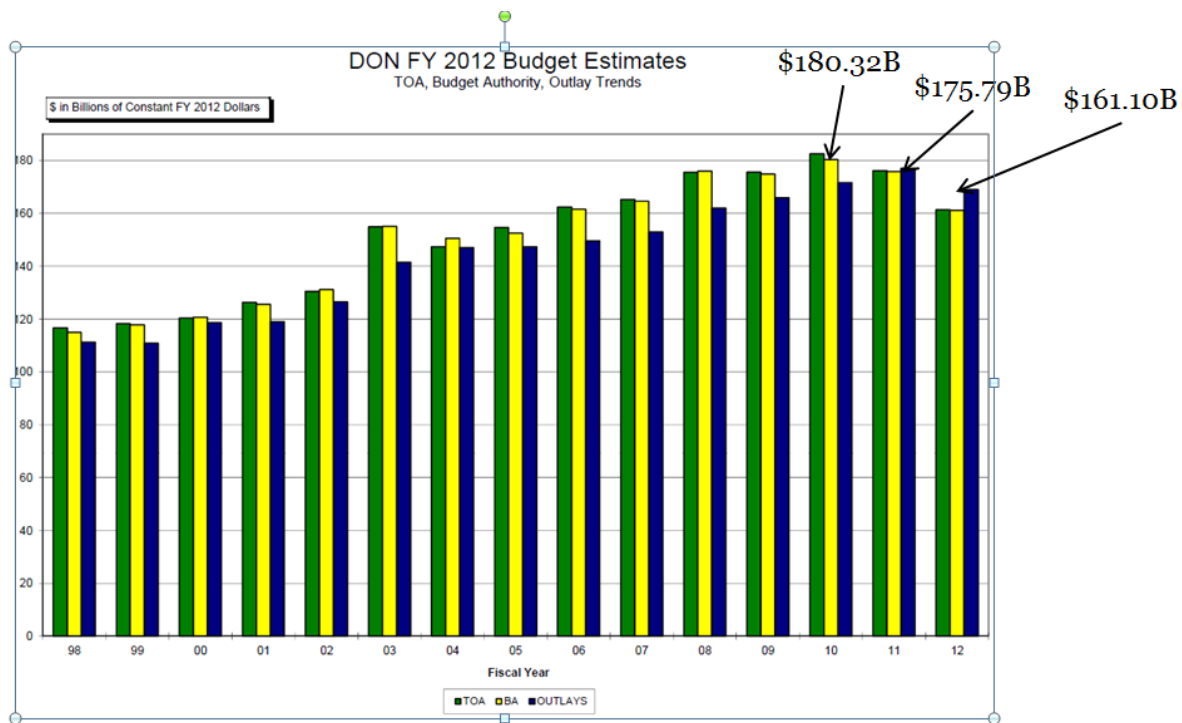


Figure 2: DoN Budget data from 1998 to 2012 (adapted from “Department of the Navy Fiscal Year Budget Estimates,” 2012)

In addition, the Navy needs to match personnel to the right tasks or positions when considering increasing technology complexity. The GAO claims that “the cost of the ship’s crew is the largest expense incurred over the ship’s lifetime” (GAO, 2003). Because of this reason, the Navy has made a lot of efforts to reduce crew size on board. The future ship classes will be operated by significantly smaller crew. New technologies are being introduced into the United States military system in order to empower enhanced performance with fewer personnel. Reduced personnel levels can result in significant financial savings for the Navy, as well as enhanced quality of life for sailors, thus helping meet the Navy’s challenges of more missions, less overall cost, and

increased competition for qualified people (Spindel et al., 2000). Therefore, clearly identifying the components of manpower cost is very critical for Navy decision makers.

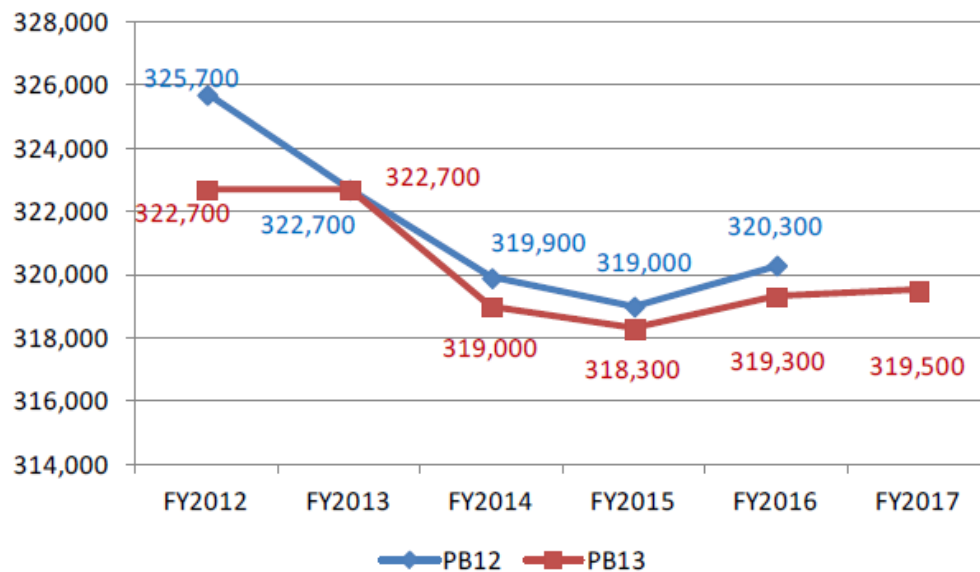


Figure 3: Active Personnel Reduction of FY 2012 to FY2017

(adapted from “Department of the Navy Fiscal Year Budget Estimates,” 2012)

Figure 3 shows the active personnel reduction trend based on DoN Budget data. Civilian manpower also will drop for the upcoming fiscal years according to the DoN Budget documents.

The following review section starts with the definition of Manpower and relationship with personnel, followed by components of the manpower life cycle cost and manpower requirement components, and then focuses on different manpower cost methods from previous research efforts.

## 2.2 Manpower Definition and Cost Components

### 2.2.1 Definition and History

According to the Department of Army (2001), Manpower includes the number of personnel of operating, maintaining, supporting and training for a system. Manpower cost analysis is an analytical approach, using different tools and techniques to develop personnel costs for various Navy systems.

According to the Human System Integration (HSI) Handbook (Booher, 2003), manpower includes determination of the number of personnel to maintain and support a new system. It also includes calculations of whether more personnel are needed than it is required by the new system.

According to Lockman (1985), manpower includes requirements for human related factors to achieve organizational goals. Manpower requirements are concerned with the numbers and skills needed to operate the Navy.

The Ship Manpower Document (SMD) is an important document for the Navy in establishing a reliable numbers for ship personnel, and in managing ship readiness. The Navy Manpower Analysis Center (NAVMAC) has a responsibility to create documents for the mission requirements of the billets when a class of ships is under development.

Currently, the increasing sophistication of weapon systems and new technology has increased the requirement for Navy Manpower. New technology also requires the Navy to have qualified personnel on board to accomplish missions.

### 2.2.2 Differences and Relation with Personnel

According to the MANPRINT Handbook (2005), Manpower and personnel are closely related. Manpower focuses on the number of persons, however, personnel focus on the cognitive and physical characteristics that need to operate, maintain, and sustain different systems. Personnel characteristics of enlisted personnel can be measured by the Armed Forces Qualification Test (AFQT) and the Aptitude Area scores determined by the Career Management Fields (CMFs).

Manpower looks not only at what types of personnel but also at how many personnel are needed to operate, sustain, and maintain a particular system.

### 2.2.3 Importance of Manpower cost

As we know, manpower cost comprises over 50 percent of O&S cost. O&S cost is a major component of total ownership cost. Therefore, it is critical to understand manpower cost in order to reduce the total ownership cost. Research has been done in an effort in to reduce manpower cost during the last decade.

Masiello (2002) conducted research in the area of identifying factors that reduce the Total Ownership Cost. Figure 4 lists these cost drivers that have the potential of reducing O&S cost. Manpower is one of the major drivers for reducing TOC in this research.

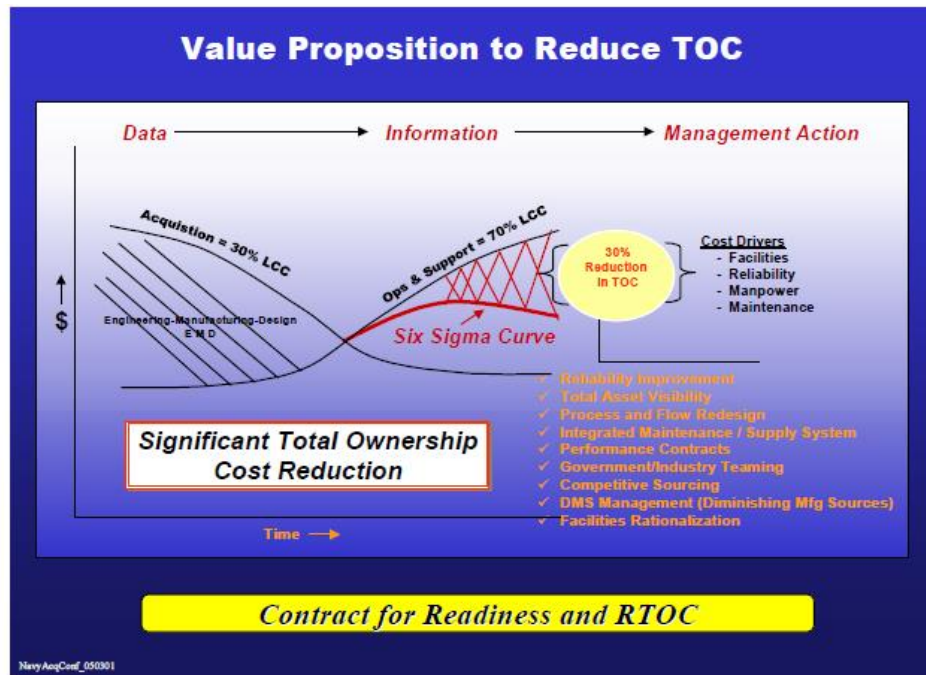


Figure 4: Manpower as a Cost Driver (adapted from “Contracting for Assured Support to the Warfighter,” Phillips, 2001)

According to Boudreau and Naegle (2004), manpower requirements are one of the cost elements which have a largest impact on TOC. The following figure shows the manpower requirements and manpower usage as they relates to TOC element influence.



Figure 5: Total Ownership Cost Element (adapted from “Total Ownership Cost: An Exercise in Discipline. DTIC Document,” Boudreau and Naegle, 2004)

### 2.3 Manpower Requirements

The purpose of studying manpower requirement is to acquire the minimal crew required to accomplish missions (Navy Manpower Analysis Center, 2007). Manpower requirements refer to the number of personnel to finish the Navy's works and accomplish these missions. Each manpower requirement defines a specific manpower that is responsible for different missions and skill levels (Navy Manpower Analysis Center, 2007).

It is critical for the Navy to determine its manpower needs for a ship readiness. Too few crews or too many crew are not good ideas for optimizing source allocation (Moore et al., 2002). Today's new technologies have different requirements for Navy manpower drivers and cost analysis. The Navy has made a lot of efforts to reduce crew size on board for more than a decade. The future ship classes will be operated by significantly smaller crew. Therefore, it is imperative to determine manpower requirements so that the Navy has the ability to establish the minimal crew size but meanwhile to achieve mission readiness. Manpower requirements also change over time as the mission changes or technology improves (Thie, 2008).

### 2.3.1 Manpower Components

Broadly, there are two types of components related to manpower cost. Manpower requirements happen at the early stage of the Navy acquisition cycle. It has to be clarified based on the workload and ship design. However, Manpower cost components provide manpower life cycle cost consideration such as basic pay, cost of training, etc. This cost has a big impact on the O&S cost.

### 2.3.2 Manpower Requirement Determination Factors

The following elements determine manpower requirements:

- (1) Required operational capability and projected operational environment (ROC/POE)
- (2) Directed manpower requirements
- (3) Watch stations



(4) Preventive, corrective, and facilities maintenance

(5) Workload requirements

ROC/POE is the most critical element to estimate manpower requirements. The ROC defines the system's mission requirements, and the POE specifies operating environment in which the unit is expected to operate (DoN, 2007). Workload factor is another key element used to calculate manpower requirements.

### 2.3.3 Manpower Cost Model Components

The AMCOS (Army Manpower Cost System) module provides components of the manpower life cycle cost. These components as follows:

- 1) Military compensation (Basic Pay and Allowances)
- 2) Civilian base salary
- 3) Officer acquisition
- 4) Recruiting
- 5) Training
- 6) Reenlistment bonuses
- 7) Retirement costs
- 8) Selective reenlistment Bonus
- 9) Other benefits
- 10) Special or premium Pay

### 11) Medical benefits

Fully understanding manpower cost drivers will allow policy makers to make appropriate decisions on future weapon systems launching. It also enables the Army to improve cost estimates and improve resource allocation. Black et al., (1992) described the model of the Army manpower cost in the diagram below.

Figure 6 showed the scope of this model. The AMCOS was designed to provide the budgetary cost of manpower requirements by skill categories, grade, cost element (e.g. compensation, retirement benefits), and congressional appropriation. The model describes the scope of estimating the cost of current and future manpower requirements for the Army including components of the active, reserve, and civilian.

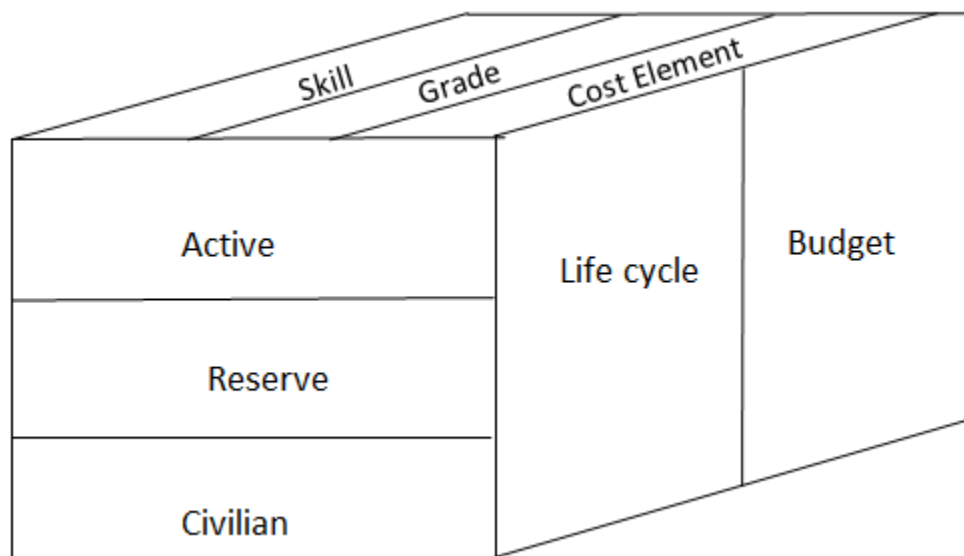


Figure 6: AMCOS Scope (adapted from “Army Manpower Cost System,” Black et al., 1992)

#### 2.3.4 Workload Categories for Manpower Requirement

It is important to clarify workload categories in order to understand manpower requirements for the Navy. The MANPRINT Handbook (2005) establishes guidance for decision makers regarding the type of workers required to achieve different missions.

According to the Navy document, operational manning (OM), own-unit support (OUS), preventive maintenance (PM), corrective maintenance (CM), and facilities maintenance (FM) are major categories to determine manpower requirement. These categories affect different types of primary workloads.

According to Moore et al (2002), the Navy manpower cost analysts interpret the workload onboard by interviewing with crew members. Crewmember workload was distinguished based on their knowledge, skills and abilities (KSA). Operational manning was the largest workload for crew members (Correno et al., 2010). Among these factors, OM make up 38% percent of workload and OUS account for another 22% of the workload. Training comprises approximately 10% of the workload.

There are some options for the Navy to reduce manpower requirements. Moore et al. (2002) described three choices reduce crew sizes including (1) technology in reducing workload (2) more reliable and experienced crew members, and (3) more efficient people to reduce redundant work.

Mannie and Risser (1984) described the very detailed process of calculating manpower requirements and training cost for different grade of officers in the Navy. The following figure shows the detail of the equation.

In Mannie and Risser's research, 77 work hours per week were scheduled for both operators and non-operators. These 77 work hours include 57.75 hours of scheduled work and 19.25 hours for Unit Movement allowance assigned for operators.

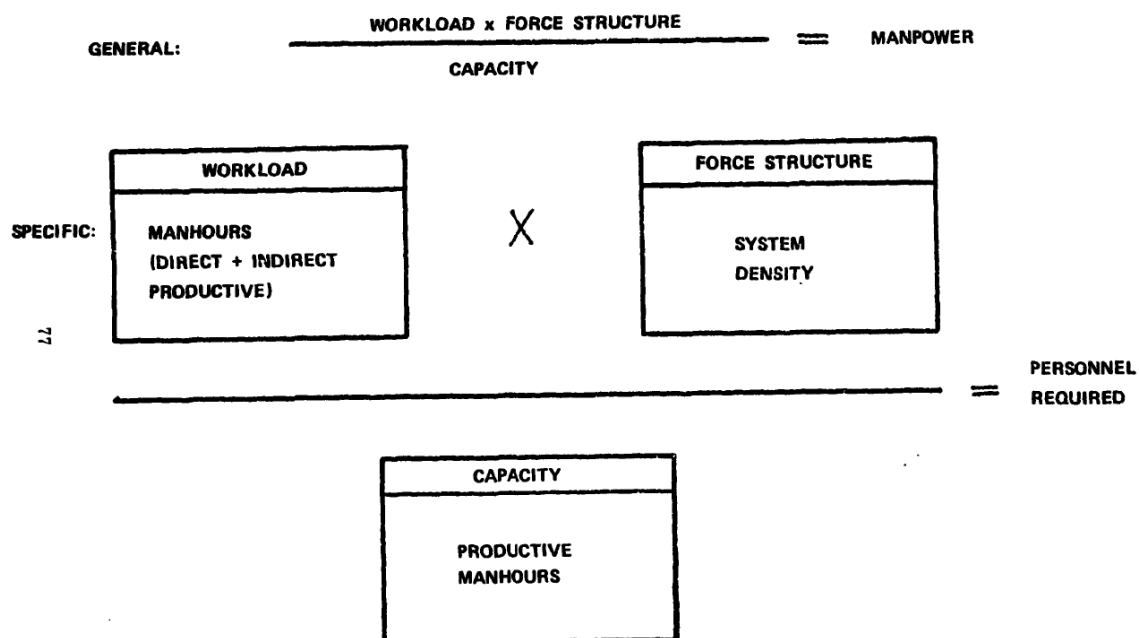


Figure 7: Personnel calculation by numbers of workload (adapted from Mannie and Risser, 1984)

The variable manpower requirements for operational and maintenance workload can then be considered separately. Mannie and Risser (1984) calculated manpower by identify workload

amount divided by the total work hours per week. OM, SM, UM and PMCS represent operational manning, scheduled maintenance, unscheduled maintenance, and preventive maintenance checks and services respectively.

## 2.4 Manpower Cost Methods

Leonard (2009) summarized four common types of cost estimating methods for different applications. These commonly used methods for estimating costs include analogy, Engineering bottom-up, parametric and the expert opinion approach. An Analogy uses the cost of similar programs to estimate the new program and adjusts it for differences. The Engineering Bottom-up method develops the cost estimation from the lowest level of the system, and then summarizes all levels. The parametric method relates cost to one or more program parameters by using a statistical relationship. Expert opinion uses the subjective matter experts to develop estimates. Table 1 compares the first three methods summarized by GAO document.

Table 1 Cost Methodologies (adapted from “Cost Estimating and assessment Guide,” GAO, 2003)

| TABLE 1: Cost Methodologies |  |   |                                   |
|-----------------------------|--|---|-----------------------------------|
| Method                      | Strength   | Weakness                                    | Application                       |
| Analogy                     | Requires few data  | Subjective adjustments                      | When few data are available       |
|                             | Based on actual data                                       | Accuracy depends on similarity of items     | Rough-order-of-magnitude estimate |
|                             | Reasonably quick   | Difficult to assess effect of design change | Cross-check                       |
| Engineering build-up        | Good audit trail   | Blind to cost drivers                       |                                   |
|                             | Easily audited   | Requires detailed design                    | Production estimating             |
|                             | Sensitive to labor rates                                   | Slow and laborious                          | Software development              |
|                             | Tracks vendor quotes                                       | Cumbersome                                  | Negotiations                      |
| Parametric                  | Time-honored   |   |                                   |
|                             | Reasonably quick   | Lacks detail                                | Budgetary estimates               |
|                             | Encourages discipline                                      | Model investment                            | Design-to-cost trade studies      |
|                             | Good audit trail   | Cultural barriers                           | Cross-check                       |
|                             | Objective, little bias                                     | Need to understand model's behavior         | Baseline estimate                 |
|                             | Cost driver visibility                                     |   | Cost goal allocations             |
|                             | Incorporates real-world effects (funding, technical, risk) |   |                                   |

The following section summarized different methods related with manpower cost for different manpower research projects. These methods comprise HSI trade-offs, cost-benefit analysis, cost-effectiveness analysis, econometric approach, linear regression method, and simulation methods.

#### 2.4.1 Human System Integration (HSI) Trade-Off

The goal of Human System Integration (HSI) is to reduce TOC and improve system performance by involving human –related areas. According to DoD instruction 5000.02 (US DoD, 2008), there are seven domains of HSI which include manpower, personnel, training, human factors engineering, survivability, habitability, and safety & occupational health. HSI is used to minimize TOC and optimize manpower at the same time. This method takes into consideration

human capabilities and limitations during the phase of system designing. The U.S. Army initially started to develop HSI tool and used the tool to support quantitative trade-offs (Booher, 2003). By considering different stakeholders' interests, HSI can improve system performance and minimize TOC (Landsburg et al., 2008). Early HSI analyses decreased cost by making the job easier and the people more effective. In order to minimize TOC and also to optimize total system performance, the DoD has directed program managers to consider HSI in the early stage of the acquisition process (DoD, 2008). The reason is that HSI considers improving system performance and reducing TOC at the same time. For example, The Canadian Defense Technology Center conducted research from 2000 to 2004 on the application of HSI during 31 Defense acquisition programs. The research led to a savings of \$3.33M overall. Sindall (2010) asserted that it is important to incorporate HSI analyses into system performance since it has a significant impact on life-cycle costs. Currently, reducing ship crews using HSI tools and concepts has become a Navy priority.

The goal of HSI analyses is to satisfy system requirements without scarifying TOC, system performance, and delivery schedule (Shattuck et al., 2011). Using the HSI method, research completed to reduce manpower include using automation to replace personnel, designing systems that have lower maintenance requirements, and reducing maintenance requirements on the ship's crew by using more shore based maintenance. Cross-training crewmembers to perform the work of other crewmembers is another suggestion that may help eliminate underutilized shipboard personnel (Scofield, 2006).

HSI has been applied in many ways for military applications. The U.S. Air force has demonstrated cost can be decreased by using HSI technology. Lizza et al (2008) did study of the F-22 Raptor associated with manpower, personnel and training and led to a \$700M cost avoidance, and subsequent approximately \$3B lifecycle savings.

HSI mainly takes into consideration human capabilities and limitations during the phase of system designing. The phased of system designing happens in the early stage of the LCC. The following figure shows these phases of LCC.

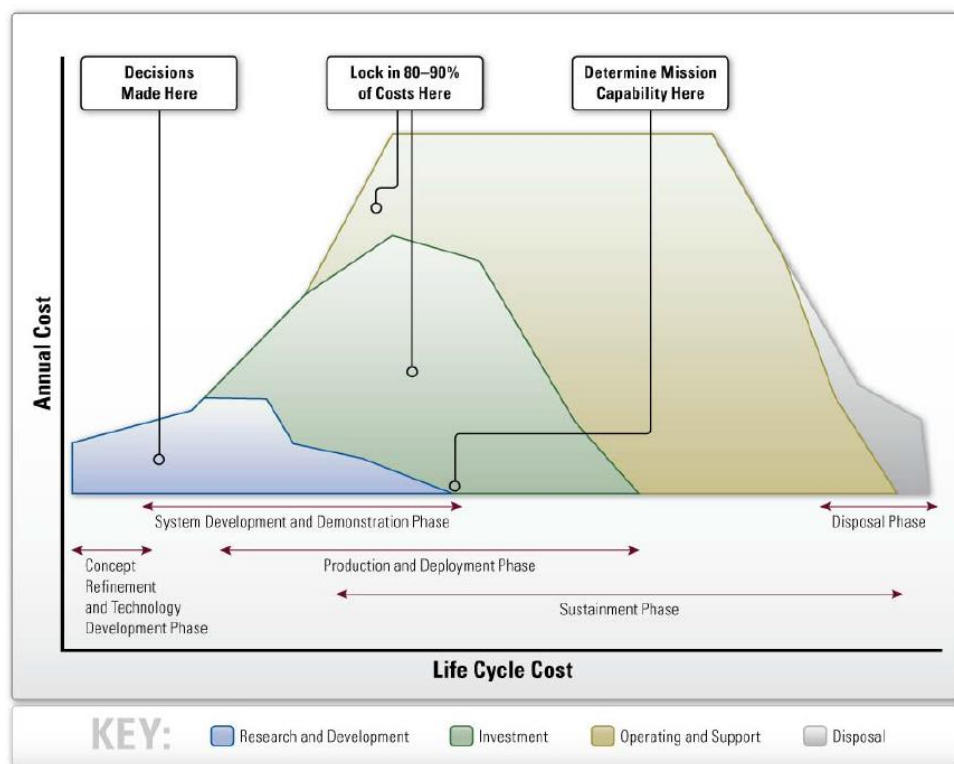



Figure 8: Life Cycle Cost (adapted from “Handbook of human systems integration,” Booher, 2003)



The successful stories by using HSI can be traced back to the 1990s. The Military started a program called MANPRINT (the Army's manpower and personnel integration). MANPRINT focuses on considering human-related domains into the system acquisition process. It started the recognition of each human component of the total system. One of goals for MANPRINT is to reduce TOC (MPT Handbook, 2005). MANPRINT is recognized as being very successful at reducing costs and improving safety and performance in technology acquisition. For example, Comanche helicopter applied MANPRINT in design and development and achieved \$3.29 billion cost avoidance in human related cost.

Another successful story applied HSI is the Light helicopter. In Booher's (1997) paper, workload and automation trade-off were specified in the flowing figure. The design of adopting a two-seat was a choice for satisfying mission performance. However, 12% more maintenance support would be required than the single-seat design because of the additional manpower requirement.

LHX



| ■ CREW WORKLOAD MODEL | <u>OVERLOADS</u> |          |
|-----------------------|------------------|----------|
|                       | ONE CREW         | TWO CREW |
|                       | NO AUTOMATION    | 263      |
|                       | AUTOMATION       | 10       |
|                       |                  | 43       |
|                       |                  | 0        |

| ■ MANCAP MODEL<br>(MANPOWER CAPABILITY)<br>(LIGHT INFANTRY DIVISION) | UNIT DESIGN | MANPOWER RQMT |
|--|-------------|---------------|
|  | AOE         | 416           |
|  | LHX         | 313           |

Figure 9: LHX: automation versus no automation (adapted from "Human Factors Integration: Cost and Performance Benefits on Army Systems," Booher, 1997)

Bost and Galdorisi (2004) specified the process that aims to reduce the workload and improve system performance by applying HSI trade-off analysis. HSI trade-off analysis include different areas. HSI trade-off attempts to use different technology, automation, and training technology to reduce manpower cost and improve system performance. Booher (2003, ch11) listed trade-off areas for manpower, training , and aptitude. Lower personnel aptitude increases training requirements.

The Air Force HSI handbook (Force, 2008) also listed tradeoffs and the relationships within and between manpower, personnel, and training domains. These tradeoffs deal with associated LCCs that apply to the proposed operations and sustainment concepts of the system.

Scofield (2006) demonstrated that there are many possible options available to ship designers to reduce the number of crewmembers onboard ship. These possible options include improving in automation, maintenance workload, training, and system capabilities. Nugent and white (2000) also described some options for the best crew manning strategy including minimizing the number of different jobs, minimizing workload and new jobs to determine overall affordability in terms of system development, training and personnel costs. In order to reduce TOC, researchers tried to develop new methods for optimizing manpower. Spindel et al (2000) attempted to find the relationship among TOC, manpower level, and ship capability. The relationship among these three variables is depicted in the figure below.

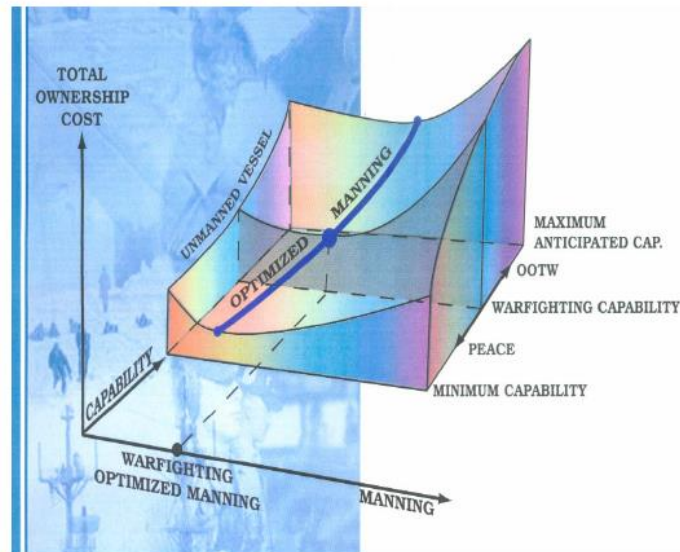


Figure 10: Optimal manning curve (adapted from “Optimized surface ship manning,” Spindel et al., 2000)

Figure 10 illustrates the tradeoffs among three variables including TOC, manpower, and capability. Finding the optimized manpower level under the constraint of TOC and keeping good war fighting capability is the key for the Navy. Simply minimizing the number of personnel on a ship does not constitute an optimal crew.

#### 2.4.1.1 Technology tradeoffs

Since this research particularly specified manpower and technology tradeoffs, the following section focuses on a review of HSI in technology tradeoffs.

In 1995, the Smart Ship program demonstrated the success in reducing manpower, maintain ship capability and improve shipboard quality of life by implementing new technology. The USS Yorktown (CG 48) was chosen to exercise this program.

Eventually the Smart Ship program achieved workload reductions in three major areas (Koopeman and Golding, 1999). These areas include:

- Policy and procedure : only core watchstation are operated all the time
- Technology: applied more automated functions in navigation, machinery control, and other systems
- Maintenance methods: used more reliable maintenance methods to reduce the PM workload

Those methods combined to reduce the weekly workload about 30 percent or a 12 person reduction for the USS Yorktown.

Although the smart ship program was tested by the legacy ship USS Yorktown, it also demonstrated new, more automated systems that can apply for this program. For both new construction and existing ships, the Navy tries to improve human and system performance by integrating HSI and other technologies. For example, a study had been conducted to determine methods to reduce manpower requirements on the Arleigh Burke class destroyers (Osga and Galdorisi, 2003). Their research also mentioned the Navy launched the Sea Power 21 transformation plan in 2003 which included three support processes for manpower and technology. With the new technology installed, the system should work cooperatively with human supervision.

Koopeman and Golding (1999) and Osga (1999) described the detail of Multi-Modal Watch station (MMWS) technology development in order to increase automation and reduce workload for Navy platforms. MMWS is an improved workstation that aims to reduce manpower

requirements by applying advanced displays and embedded intelligence. Correno et al (2010) described a method of developing improved human computer integration (HCI) to allow one operator to control more than one unmanned vehicles. The HCI achieves this by reducing cognitive and visual workloads on each vehicle. Thereby, it also achieves a substantial manpower savings.

Thie (2008) summerized options for DoD in trade workforce. These options include:

- (1) Trade one workforce for another. Under some circumstances, replacing the highest-cost workforce into a cheaper one.
- (2) Trade non-experienced sailors for experienced sailors. It can be achieved by using a smaller but more-experience workforce.
- (3) Reduce manpower investement in a long run. It can be achieved by increasing short-term material acquisition cost for technology to reduce the long-term manpower cost.

Among these three options, the third option is the trade-off between technology and manpower.

Bost and Galdorisi (2004) also studied this using HSI to reduce manning. In their study, they leveraged HSI in existing ship systems like the DDG-51 ship. They identified workload levels by analyzing of the tasks of sailors.

Scofiled (2006) studied manpower and automation tradeoffs. In his paper, he listed the different levels of automation and defined them in a very detailed way. He also illustrated that automation is the largest factor having impact on the crew size. His model uses ship length, level of

automation, level of maintenance as inputs. The output is the crew size in his model. Figure 11 depicts this information:

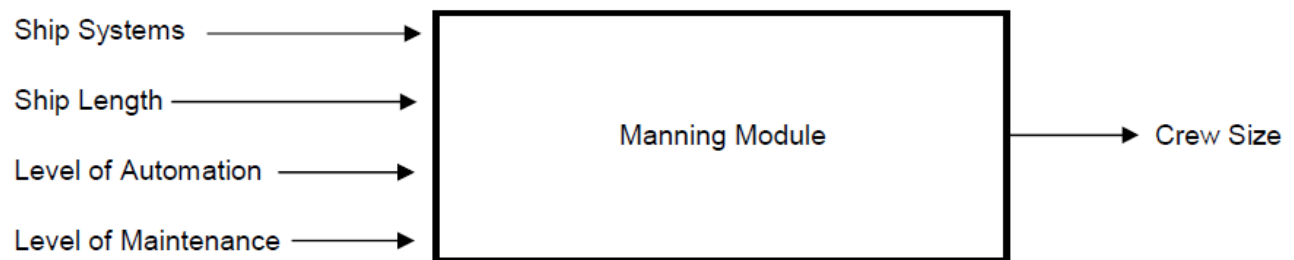


Figure 11: Manning module Block Diagram (adapted from “Manning and automation model for naval ship analysis and optimization,” Scofield, 2006)

Douangaphaivong (2004) did a study on manpower reduction for the Littoral Combat Ship (LCS). In his research, technology leverage and workload transfer methods are discussed. Technology Leverage applies the Smart Ship technologies to reduce the manpower requirements. Workload Transfer seeks to reduce workload onboard. The following figure shows the workload transferring illustration to reduce manning initiatives onboard for the study of LCS.

Obviously, it is a good way for the Navy to reduce manpower by implementing new technology. Many researches had been conducted to develop platforms to reduce manpower for future Naval systems. HSI initiatives have been implemented into Naval system design and development in order to achieve manpower reduction.

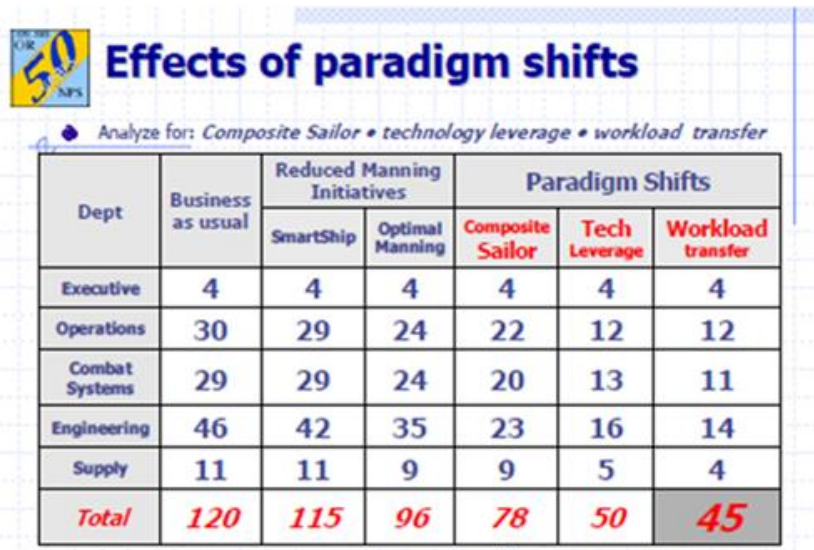


Figure 12: Effects of paradigm shifts on LCS Sea frame manning (adapted from “Littoral combat ship (LCS) manpower requirements analysis,” Douangaphaivong, 2004)

#### 2.4.1.2 Top-down Requirements Analysis

The top down requirements process has been outlined in the research of Malone and Carson (2001). First, the HSI high drivers and lessons learned from comparable legacy systems are identified. Next, mission requirements are identified for different scenarios. Following this, an iterative process is identified to reduce workload and increase human performance. Human performance and workload are assessed via modeling and simulation and then tasks and task performance requirements are analyzed. The affordability and risk of each contemplated improvement is also assessed. Finally, the requirements of manpower, human performance, health and safety complete after all processes are complete (Lockett and Duma, 2009).

Malone and Carson (2003) described the method of reducing manpower requirements from 47 to 12 by using this Top-down analysis.

In the research of Malone and Bost (2000), there are ten major steps involved into this manpower reduction process. Johnson et al (2005) used the top-down requirement analysis method to study LHD amphibious-assault-class ships manning reduction. Crew requirements start at zero under this method. Table 2 shows the detail of the method they used in their study. They identified workload-reduction drivers using HSI tools, for example, better information displays (e.g. helmet-mounted displays (HMD)) and information management for simplifying communications. In their paper, Johnson and his colleagues listed ten innovation technologies for the Navy LHD amphibious system. Some technologies have a higher estimated return on investment and relatively low risks. They are listed as follows:

- Reduction/transfer of OUS and maintenance involves currently available automation technology and transferring work ashore.
- Reductions of machinery operators and shaft alley watches can be facilitated by remote sensing equipment, cameras installed to support remote monitoring, and the use of remote operator panels designed to monitor multiple pieces of equipment.
- Improved well-deck handling procedures reduce the high-driver manning requirements.

Their study results show that a reduction in manning of nearly 35% can be accomplished by using different technologies and can produce an estimated life-cycle cost saving of over \$1 billion per ship.



Table 2 Top-down requirement analysis task and Northrop Grumman approach (adapted from “Human Systems Integration/Manning Reduction for LHD-Type Ships,” Johnson et al, 2005)

| Top-Down Requirement Analysis Task                                      | Northrop Grumman Approach  |
|---|--|
| 1. Functional analysis  | Use LHD 1 Required Operational Capabilities and Projected Operational Environment documents                  |
| 2. Identify high-driver functions                                       | Use LHD 8 Preliminary Ship Manpower Document (PSMD)  |
| 3. Analyze mission requirements via scenario                            | Use subject-matter experts (SMEs) to generate two-week LHD scenario  |
| 4. Conduct mission/function analyses                                    | Use LHD 8 PSMD (including Battle Bill), LHD 4 Watch Quarter and Station Bill, SME input                      |
| 5. Allocate functions and define role of crew members                   | Solicit SME inputs, analyze gaps between projected and actual feasibility                                    |
| 6. Identify workload-reduction concepts                                 | Conduct literature review, solicit SME inputs  |
| 7. Assess affordability and risk potential of reduced-workload concepts | Conduct literature review, calculate “cost of sailor,” analyze gaps between projected and actual feasibility |
| 8. Define task networks and analyze task requirements                   | Use Northrop Grumman Task Analysis database, Complete Crew Model (CCM)                                       |
| 9. Conduct simulations to assess human performance and workload         | Use CCM  |
| 10. Develop and validate ship manning model                             | Use Northrop Grumman Task Analysis database, LHD 8 manning requirement list, LHD 8 PSMD                      |

#### 2.4.1.3 Personnel and training trade-off

Booher (2003) expressed that the trade-off space in training associated with time, quality, and cost. Especially the trade-off is between cost and time due to the system performance standards. For example, managers may raise the instructor-to-student ratio in order to make the training time shorter. However, this action will increase cost for paying instructors. Another alternative is to reduce the training time in order to decrease training cost.

#### 2.4.2 Cost-Benefit Analysis (CBA)

Cost-Benefit Analysis (CBA) is a technique for decision makers to determine how much cost spent comparing with amount of benefits. CBA has many applications for decision makers such as finance, economy, and marketing decisions that can be interpreted in terms of dollars. Three basic types of benefits include cost savings, cost avoidance, and productivity improvements (Department of the Army, 2001). Most researchers agree with Swope (1976) that a CBA process should include the following steps:

- Formulate Assumptions
- Determine Alternatives
- Determine Costs and Benefits
- Compare and Select Alternatives
- Conduct Sensitivity Analysis

In Boudreau (1990)'s paper, he used the CBA method to do the personnel and human resource analysis. Boudreau believed that it was vital to compare the money spent on human factors work and the money obtained from benefits in the current economic climate. One of the CBA methods addresses the money value of investing some resources (e.g. technology) to improve the performance of system or manpower. CBA gives decision makers different options in maximizing benefits.

Table 3 Example of CBA method (adapted from “Cost-Benefit Analysis Applied to Personnel/Human Resource Management Decisions,” Boudreau, 1990)

| <u>Cost Factor</u>                            | <u>Option A</u>     | <u>Option B</u>     |
|---|---------------------|---------------------|
| Development Fees (Year 1 only)                | \$20,000            | \$30,000            |
| Staff Program Development Time (Year 1 only)  | \$15,000            | \$5,000             |
| Extra Staffing Administration (5-Year total)  | \$250,000           | None                |
| Recruiting/Selection Materials (5-Year total) | \$50,000            | None                |
| Increased Compensation Costs (5-Year total)   | \$18,720,000        | \$23,712,000        |
| Trainee Time (Assuming \$10/hour pay level)   | None                | \$4,000,000         |
| Trainee Materials (5-Year total)              | None                | \$25,000            |
| Training Tuition (5-Year total)               | None                | \$1,500,000         |
| <b>Five-Year Total Cost Estimate</b>          | <b>\$19,055,000</b> | <b>\$29,272,000</b> |

The table above gives us examples of two options and major cost factors for these two options and then compares how much benefit (e.g. Skills earned) for each alternative. Finally decision makers make the decision based on the calculation of two options. This method also calculates the Break-Even (BE) points for each alternative. If benefits obtained are less than the BE points, then the alternative does not need to be considered part of the final outcome.

Fleming (1997) studied the cost and benefits for Smart Ship technology. Smart ship was mentioned as a technology for manpower reduction in his research. The project aimed to reduce cost in shipboard operation and control. It used common sense approaches, along with “off the shelf” technology to reduce manpower requirements for watch stations. In the conclusion of his paper, Fleming asserted that the Smart Ship technology can achieve a maximum saving of 0.54 percent of the total budget for the DoN using FY 1996 dollars. Figure 13 reflects personnel to ship ratio changing over time.

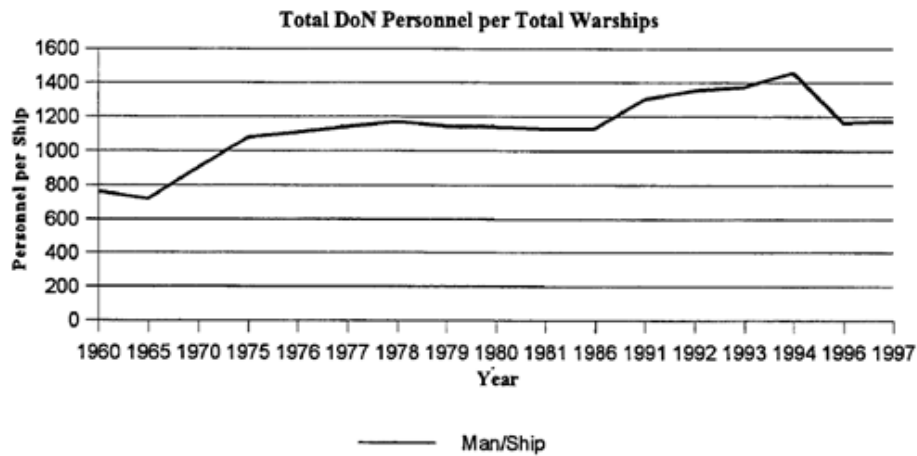


Figure 13: DoN historical number of personnel per ship (adapted from “The Cost and Benefits of Reduced Manning for US Naval Combatants,” Fleming, 1997)

#### 2.4.3 Cost-Effectiveness Analysis (CEA) and Cost-Effectiveness of Training (CEAT)

CEA is used in the DoD to make decisions regarding alternative courses of action where the outcomes affect military performance (Simpson, 1995). Examples are choosing among a set of alternative weapon systems, weapon system upgrade programs, and training methods. The definition of CEA is to estimate and evaluate of the military value associated with alternatives for achieving defined military goals. CEA is used to help meet military goals rather than CBAs which are public goals. Orlansky (1979) used CEA to evaluate the cost and effectiveness for military training back to 1979.

Training cost is one of the largest impacts on manpower cost. Adams and Rayhawk (1988) did a study on time saved in training on a weapon system by substituting less expensive training technology. Thereby, the selection of training technologies is important based on their studies. Training performance can be measured, for example, by scores on tests, number of program

graduates, or measures of on-job-performance. In his research, training costs play an important role in Cost-Benefit analysis along with training effectiveness. The determination of these costs is a multidisciplinary process which should involve psychologists and training developers. Cost estimation should take into account several economic factors such as fixed and variable costs, Time value of money, Opportunity cost, sunk cost, discount rates, constant and current dollars. Opportunity cost and sunk costs are related with training cost. In their research, training effectiveness ratio (TER) can be expressed by time. By comparing new training technology in time saving, decision makers can determine whether the new training technology is better than the alternatives.

$$TER = (W - W_d) / D$$

**W = Training Time to Criterion on a Weapon System  
Without Using an Alternative Training Technology**

**W<sub>d</sub> = Training Time to Criterion on a Weapon System  
Using an Alternative Training Technology**

**D = Time on the Alternative Training Technology, e.g.  
training device, simulator, computer-assisted  
instruction**

Figure 14: Training effectiveness ratio equation (adapted from Adams and Rayhawk, 1988)

This method is heavily used for evaluating training effectiveness. DoD invests heavily in training every year for manpower readiness. In Simpson's (1995) research, he pointed out that the Military Manpower Training Report indicated that the cost of individual training of military students for FY94 accounts for approximately 5.6% of the DoD budget (\$14.2 B). DoN's budget will continually decrease the spending on training and education, for example, the training and education budget decrease approximately \$0.2 billion for the budget year of 2013.

Table 4 lists six categories of training. Among these training categories, specialized skill training is the largest training category according to DoD.

Table 4 Distribution of Training Load (adapted from DoD report, 1997)

|                                    | FY96           | FY97           |
|------------------------------------|----------------|----------------|
| <b>Training Category</b>           |                |                |
| Recruit Training                   | 35,782         | 37,621         |
| One-Station Unit Training (Army)   | 9,576          | 10,559         |
| Officer Acquisition Training       | 18,689         | 18,604         |
| Specialized Skill Training         | 97,874         | 102,526        |
| Flight Training                    | 4,034          | 4,113          |
| Professional Development Education | 12,607         | 12,738         |
| <b>Total</b>                       | <b>178,562</b> | <b>186,161</b> |

CEAT is the specific form of CEA used in the DoD to make decisions associated with alternative courses of action for training. Effectiveness from training can be measured by shortening task completion time. The formula was presented by Simpson (1995) in the following form:

$$CTER = \frac{(Y_c - Y_x)}{X} \quad (1)$$

Y<sub>c</sub>: time for a control group

Y<sub>x</sub>: corresponding time for an experimental group

X : the time

#### 2.4.4 Econometric approach

Economists make evaluations based on supply and demand. Warner (1981) did a study regarding Navy Manpower research and reviewed the Navy manpower system market in terms

of supply and demand. He used an economic framework for analyzing Navy Manpower problems. Manpower was measured by quality, skill or experience level, sex, etc.

In his research, supply determinants include higher military pay, higher unemployment, more recruiters, and more advertising. The Navy determines its manpower demand(requirements) for most ships and aircraft squadrons by combining a statement of the required operating capability, staffing criteria established using management engineering techniques, and the Navy standard work week.

Warner's research studied an overall review of Navy labor supply and demand.

#### 2.4.5 Linear Regression method

Ting (1993) built a mathematical relationship for the Navy Manpower Operation and Support system based on the data of 652 ships of acquisition cost in 1992 dollars. He grouped 652 ships into 11 groups and calculated the average annual pay of both officers and enlistees. He assigned manpower as the dependent variable, the number of officers (OFFNAVY) and enlistees (ENLNAVY) were the independent variables for each ship. The coefficients of these variables represent the average annual pay for officers and enlistees respectively. The following equation shows the relationship of variables. The number of personnel on board a ship is proxy for ship size and ship equipment.

$$Manpower = \alpha_0 + \alpha_1 OFFNAVY + \alpha_2 ENLNAVY + \epsilon \quad (2)$$

Wang (2012) described workforce planning as a way to estimate numbers of qualified personnel at the minimal cost. Wang (2005) also used the Linear Programming (LP) to determine workforce numbers.

#### 2.4.6 Simulation method

##### 2.4.6.1 Agent-based modeling

Trifonov et al (2005) used Agent-based modeling in developing the manpower and personnel system for the Navy. The model captured the dynamics of sailor recruitment, training, retention and their performance during missions as well. By describing an agent's properties (e.g. sailor, recruitment, training, retention, ship, watch station) in their model, the model tried to improve the understanding of existing policies and potentialities to design new policies for the Navy.

##### 2.4.6.2 System Dynamics modeling

McCue (1997) developed system dynamics models for the labor determination of ship building. This workforce is reduced by normal attrition and layoffs. It is increased by newly trained workers after a certain training time. Attrition is set at approximately 10% per year. In his model, the available workforce contributed to the number of project labor and planned work remaining for the decided desired labor force.



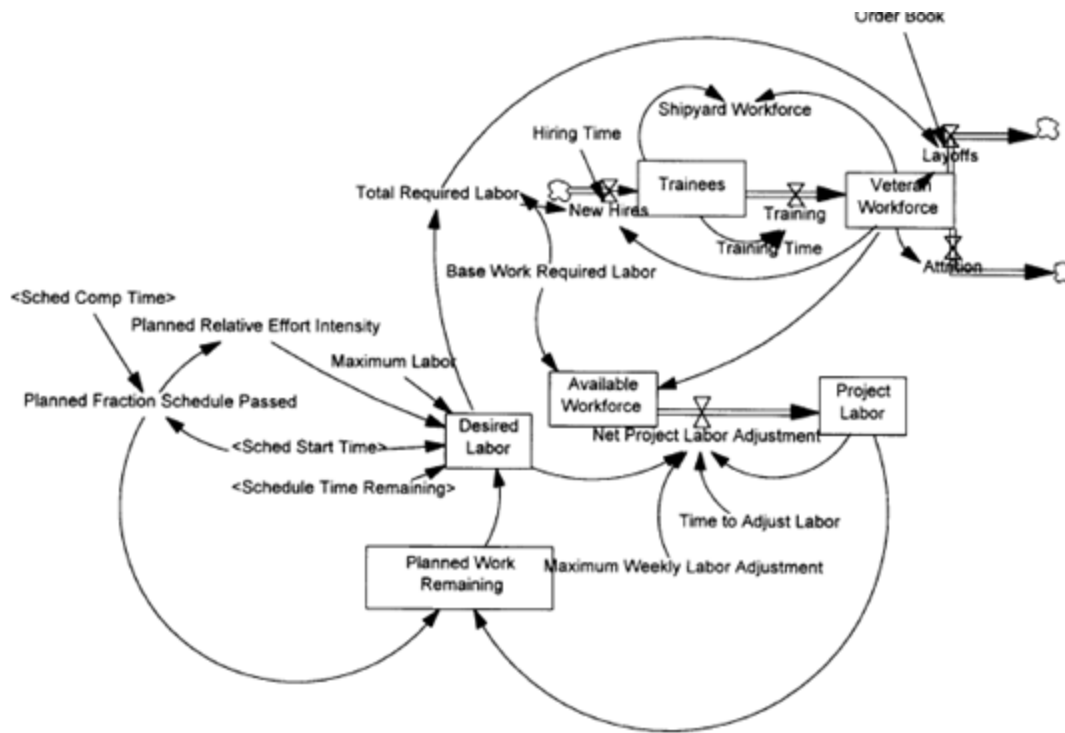


Figure 15: Labor Determination (adapted from McCue, 1997)

Yang et al. (2010) constructed a system dynamics modeling approach for human resources for the GE Company. Figure 16 showed these variables in this GE human resource model. These major variables include hiring rate, job loading, and investment in human resource, employee fear, and employee pressure.

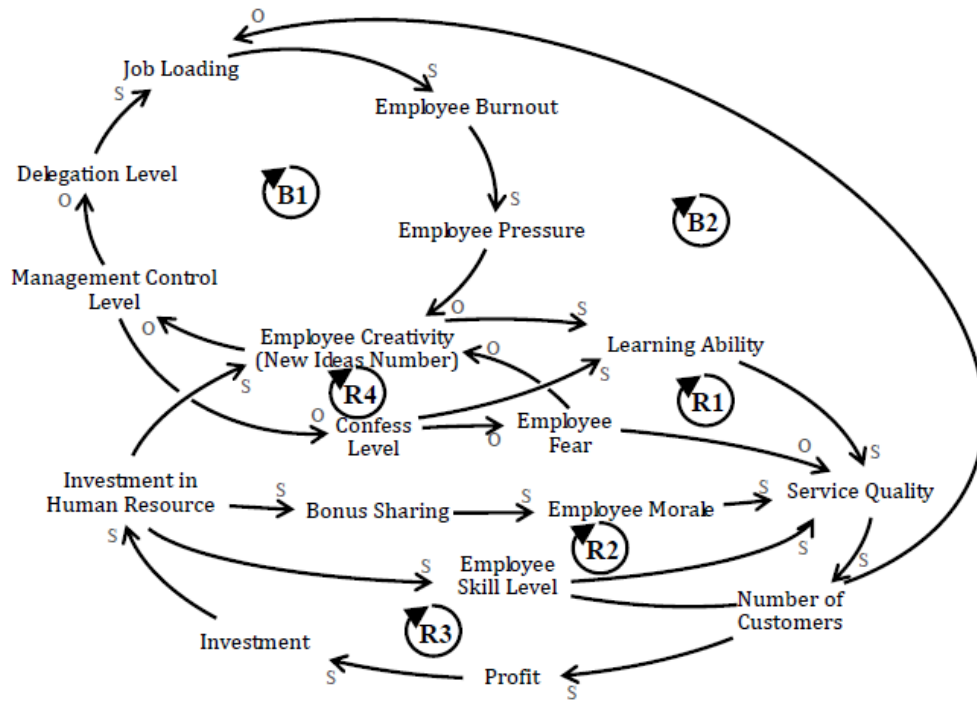


Figure 16: GE's human resource model (adapted from Yang et al., 2010)

An and Ren (2007) used the system dynamics modeling approach to capture behaviors of workforce planning. The goal of the workforce planning is to estimate numbers of qualified personnel at the minimal cost to accomplish organizational performance.

The following chapter provides additional details of System Dynamics Modeling methods for manpower cost.

## **CHAPTER THREE: SYSTEM DYNAMICS MODELING LITERATURE REVIEW**

### **3.1 Introduction**

This chapter discusses system dynamics modeling and various applications related to the human factor, human performance and human system integration related fields. System dynamics modeling was developed at MIT in 1956 and deals with how things change through time (Forrester, 1996). It was developed to understand how policy changes impact the dynamics of corporations by managers or policy makers (Sterman, 2000). System dynamics also has the ability to help managers and decision makers better understand various dynamic behaviors and to make better decisions by testing different scenarios. The strategy of system dynamics modeling is to interpret system structure by using Causal Loops and Stocks and Flows over a period of time (Sterman, 2000).

System dynamics has various applications that include business aspects such as organizational performance, financial, cost estimation, marketing and supply chain. However, System Dynamics has been increasingly used in psychology and human factors such as human reliability in nuclear power plant (Chu, 2006) and safety and risk management (Dulac, 2005). Winch (2001) studied the challenges in management related to experienced staff.

This chapter described the system thinking method first which originally system dynamics developed from, and then emphasized the system dynamics applications in many fields focusing on human performance, human factors and human system integration. In the last part of the

chapter then briefly summarized several major system dynamics software in the current system dynamics simulation community.

### 3.2 System Thinking and System Dynamics Method

System thinking allows us to see how things interrelate with others (Senge, 2000). System dynamics modeling was developed from system thinking ideas. It started from the work of Jay Forrester, who uses it to study the behavior of various components interrelated each other in the system (Forrester, 1961). A system dynamics model describes the dynamic behavior for a system regarding a particular problem. Currently this method is widely used to analyze and understand complex behaviors of systems. In the system thinking, mental models are used by managers and decision makers. Decision makers use these models in their daily decision making processes.

In system dynamics, mental model addresses our beliefs and describes how a system operates, behaves, and the time horizon in the model (Sterman, 1994).

### 3.3 Applications of System Dynamics

#### 3.3.1 Overall Applications

The System dynamics model has many applications in social science and engineering fields. System dynamics has also been used in modeling business and manufacturing industry behaviors (Goncalves, 2007). These applications are as diverse as project management (Lyneis and Ford, 2007), Supply Chain Management (Killingsworth et al., 2011; An and Ramachandran, 2005),

supply chain in army repair system (Fan et al., 2010), process improvement (Morrison, 2007), conflict management (Choucri et al., 2005), solid waste forecasting (Dyson and Chang, 2005), and many Civil engineering applications, such as effects of project personnel changes, rework, conflict management (Ng et al., 2007), and road maintenance budgeting (Bjornsson et al., 2000).

It has also been used for the U.S. space program (Dulac et al, 2005), mining industry (Cooke, 2003), aviation systems (Hustache et al., 2001), and energy power systems (Kadoya et al., 2005).

In addition, managers use it as a decision making method to focus on measuring project performance such as target schedule, quality, and progress (Lyneis and Ford, 2007). These applications seek to find solutions of assuring that projects meet their performance metrics (Ford and Sterman, 1998).

This chapter emphasizes the system dynamics modeling in system or organizational behaviors, human performance, and human system integration. The following sections demonstrate these applications.

### 3.3.2 Improvement in System or Organization Behavior

System dynamics has also been used in modeling system or organizational behaviors. There are several examples here which can be listed:

1. System dynamics is widely used in improving organizational performance. Morrison (2007) used System Dynamics modeling to simulate accumulated experience in order to improve productivity for an organization. In his paper, a learning curve is simulated for learners who

try to accomplish ongoing work while also meeting the challenge of learning new skills in an organization. In another paper, Morrison (2008) examined dynamics of process improvement by developing the causal loop diagram. Figure 17 shows the relationship between Net Process Throughput (organizational performance) and Worker Effort. The greater the Net Process Throughput is, the fewer gaps there will be. However, if the Throughput gap increases, Worker Effort will increase, and eventually training and process experimentation will need to increase also.

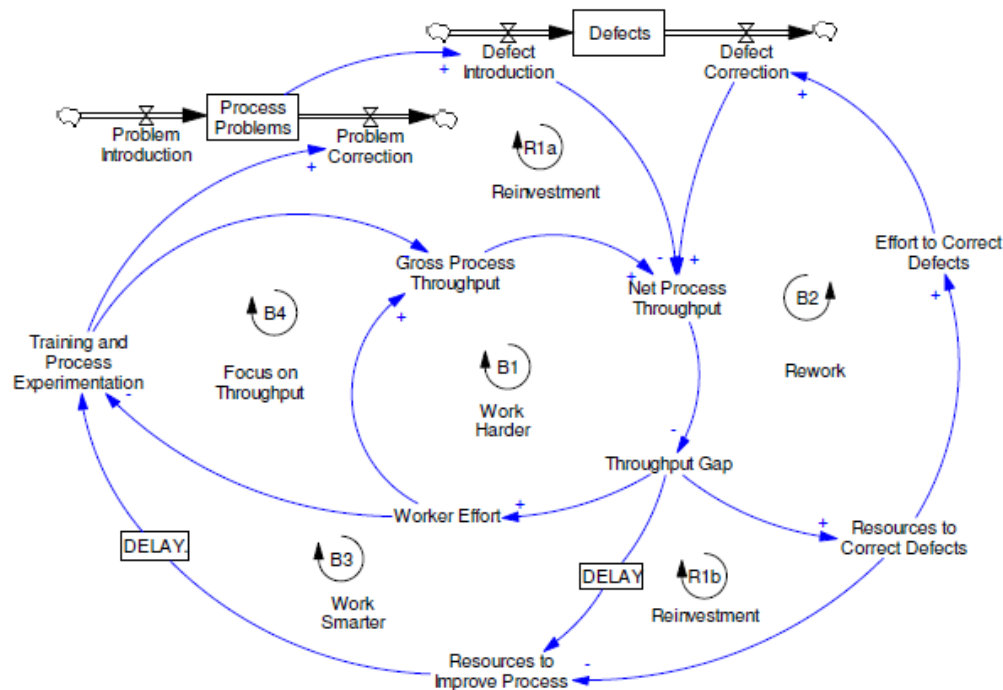


Figure 17: A model of process improvement (adapted from Repenning and Sterman, 2002)

2. System Dynamics is also used in the health organization performance assessment.

McDonnell et al. (2004) used SDM to measure the health performance for the World Health Organization (WHO).



#### 4. Organizational performance

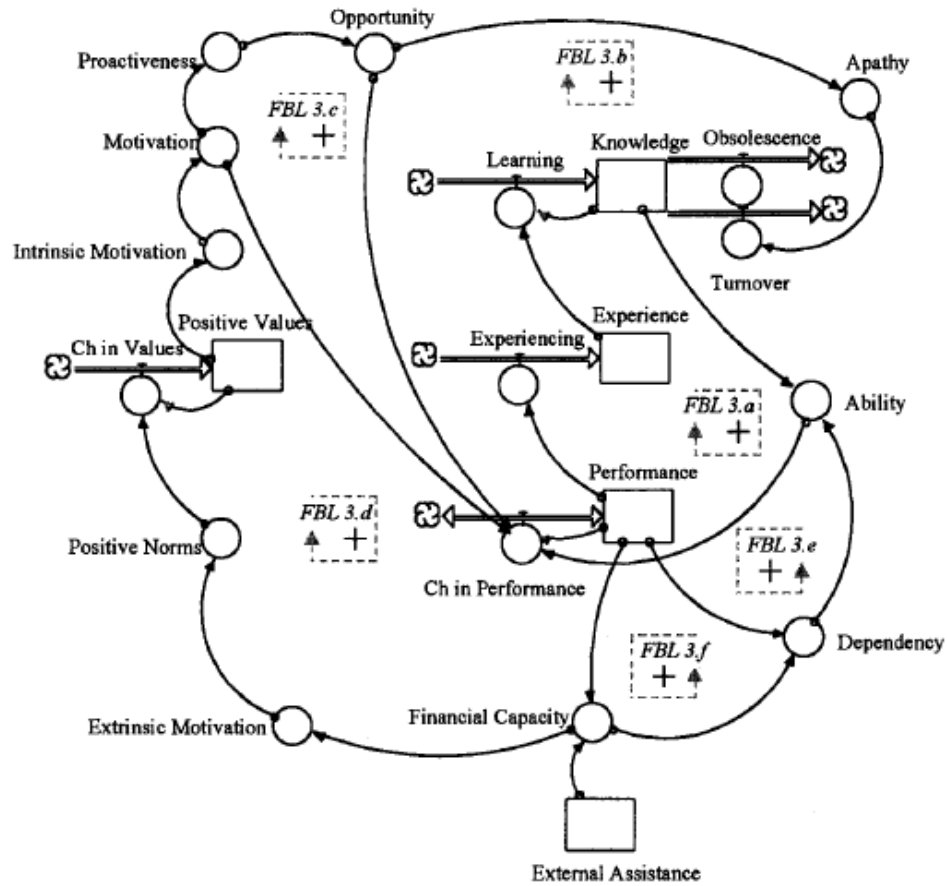


Figure 19: Organization Performance (adapted from Bajracharya et al., 2000)

Bajracharya et al (2000) described that increased motivation levels and opportunity decrease apathy and increase job satisfaction. Organization performance can be achieved through effective training and learning behaviors in the research.

In addition, System Dynamics Modeling is increasingly used in military and defense systems.

The subjects areas include weapon system planning (Fan et al., 2010), military operation



planning (Morrison, 2007), and preparedness and training (Coyle et al., 1999; Linard et al., 1998; McLucas and Linard, 2000).

### 3.3.3 System Dynamics in Human Performance (Human Reliability)

Modeling human performance and human factors are difficult work to accomplish. In order to accomplish it, researchers have used different methods to conquer this difficulty. System Dynamics Modeling is used to measure human performance in many ways, the following describes the different ways that system dynamics has been used in applications.

1. Human Reliability analysis started during WWII when it was used to increase system safety and availability analysis in military weapon system development. In Chu's thesis (2010), he used System Dynamics modeling to measure human error probability (HEP) and used it as a human performance measurement linked to Nuclear Power Plants. HEP is studied in the field of human reliability analysis (HRA) as well as in probabilistic risk analysis (PRA) (Chu, 2010). Chu studied human actions and how these actions impact system performance and reliability. In his paper, Chu (2010) listed the factors which have an impact on human performance. Table 5 lists the details of these factors.

Table 5 Performance shape factors (PSFs) lists (adapted from Chu, 2010)

| <b>Factor Names</b>                   | <b>description</b>  |
|---------------------------------------|---|
| Available time                        | The amount of time that an operator has to work on an event.  |
| Stress and stressors                  | Stress has negative influence on human performance.   |
| Experience and training               | Refer to the operators past skills and future skills needed to fulfill a task.  |
| Complexity                            | How difficult the task is to perform.   |
| Ergonomics or human machine interface | The layout, display, controls, quality and quantity of information from instrumentation.  |
| Procedures                            | Formal operating procedures for specific task   |
| Fitness for duty                      | Consider whether an individual has ability both physically and mentally to perform the task.  |
| Work processes                        | Including internal organizational activities such as work planning, safety culture, communication, management support and policies. |

2. Wang and Tu(2012) explored the process of how a team can improve its performance according to a changing environment. All individuals in a team contribute to team performance. Different performance levels imply that members need to invest different cognitions (such as

memory, information processing, and attention, etc). High work performance will require the team to invest more cognitive resources. However, the resources of cognition is equivalent to increasing the cognitive load . The higher the performance difference, the more cognitive resources are needed to be invested. Team performance will increase through increasing the cognitive load. Figure 20 shows the relationship between cognitive load, performance gap and cognition resource allocation.

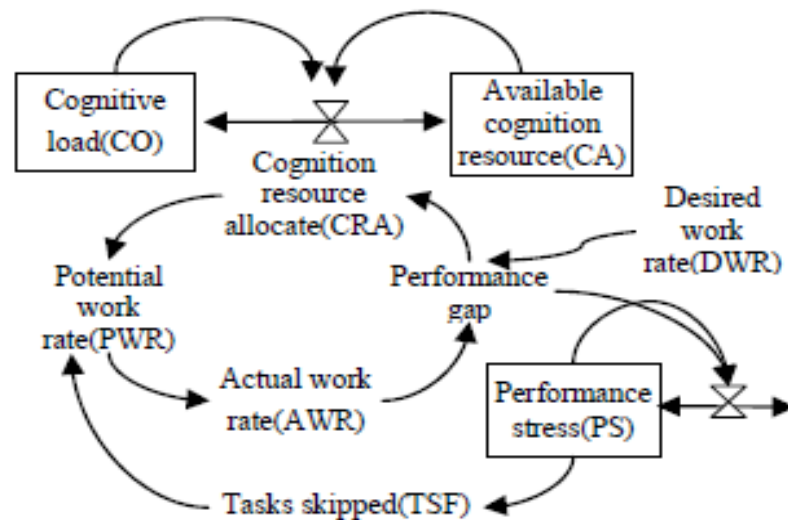


Figure 20: Process of Performance Adjustment (adapted from Wang and Tu, 2012)

3. Yu et al. (2004) developed a model of assessing nuclear safety by considering human factors in a nuclear power plant. Those variables include morale, attitude, training, employees, and workload. In their paper, they sought to identify organizational factors and measure how these factors affect human performance.

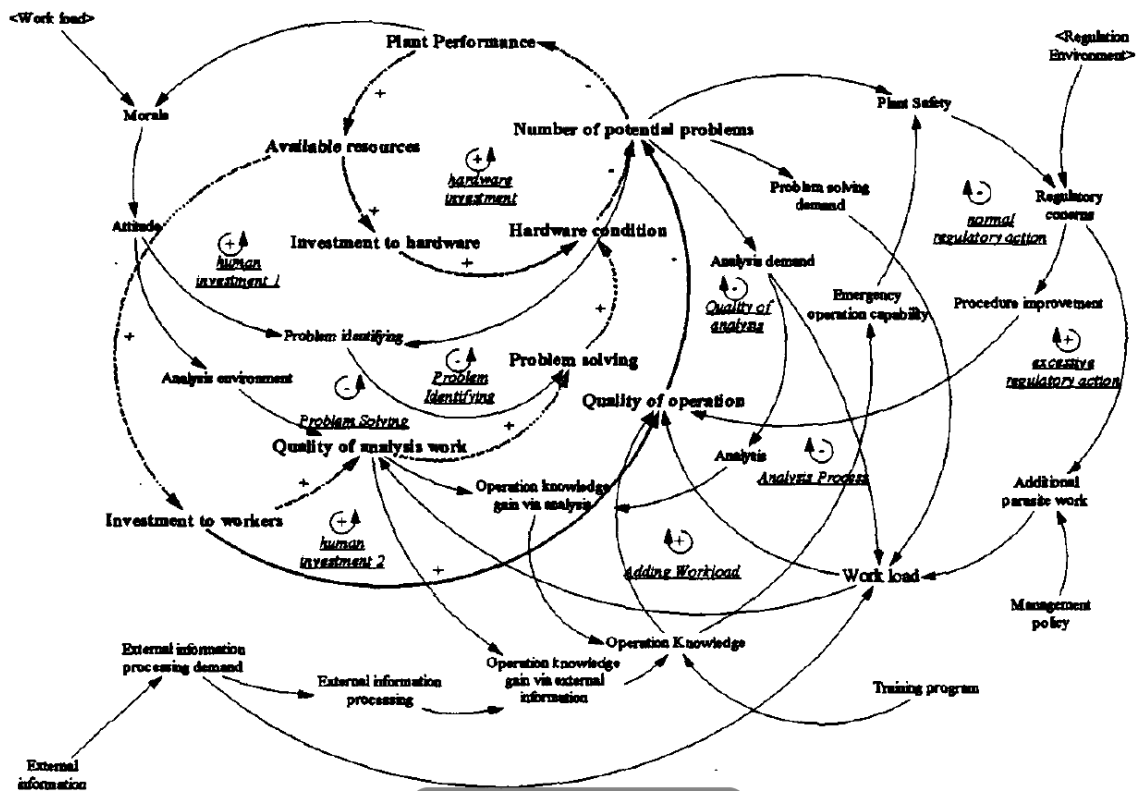


Figure 21: Nuclear Power plant performance loop (adapted from Yu et al., 2004)

### 3.3.4 System Dynamics in Human Factors

#### 3.3.4.1 Measuring Stress

Human Factors can be described as observing people at workplace. It studies the intersection between people, technology and work (Woods and Dekker, 2000). Human Factors can also be described as how technology and organizational change transforms work into systems.

Morris, Ross and Uliuru (2010) measure stress levels via Emotional Stability, Perception, Locus of Control, Coping, Cognitive, and Biological level in their paper. For example, they correlated stress and emotional stability: as cortisol level increases, anxiety increases, and then emotional

stability decreases immediately. Finally cognitive stability decreases along with emotional stability.

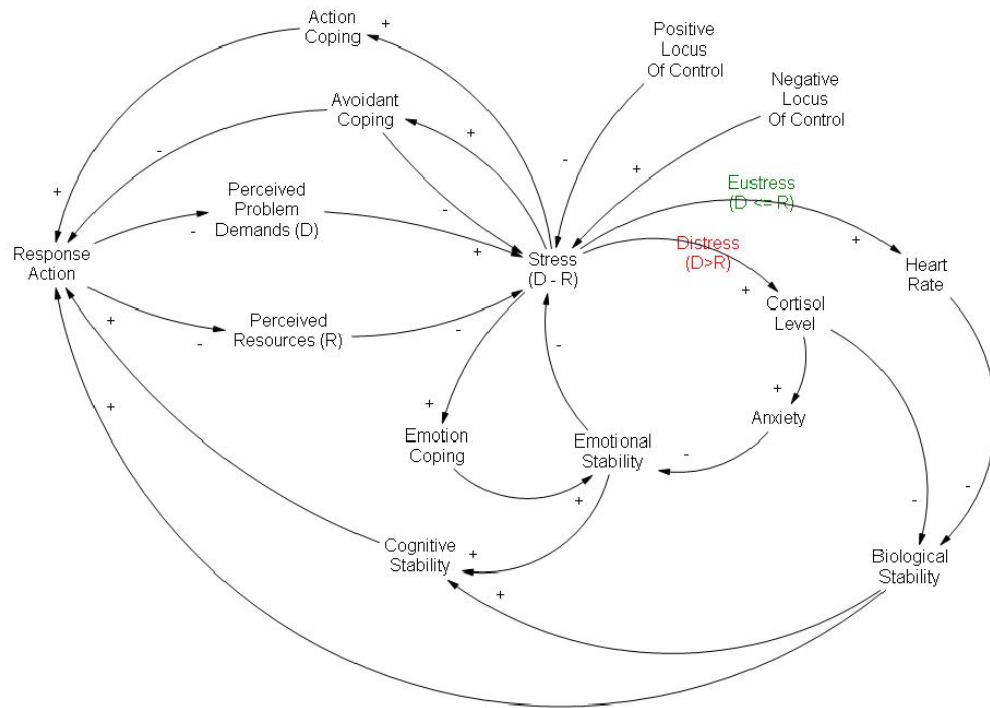


Figure 22: A causal Loop diagram for stress (adapted from Morris, Ross and Ulieru, 2010)

The figure 22 showed the relationship between these factors as they relate to stress. Stress is measured by the perceived demand and perceived resources according to this paper's theory. If perceived demand is higher than perceived resources, the Stress level increases. Otherwise, the Stress level decreases.

### 3.3.4.2 Measuring Fatigue and Work Errors

1. Herweg and Pilon (2001) used System Dynamics to measure workforce, work errors and fatigue. Figure 23 described the details of the cause and effect in a produce design process.

Attrition is predominantly the result of fatigue due to increased workloads. As the work-to-do increases, the workforce required increases. The new-hires who enter into the workforce are often inexperienced and produce more errors in their work as they learn while doing. The increased work errors lead to an increase of rework. Finally continued fatigue leads to attrition and an overall reduction in the workforce.

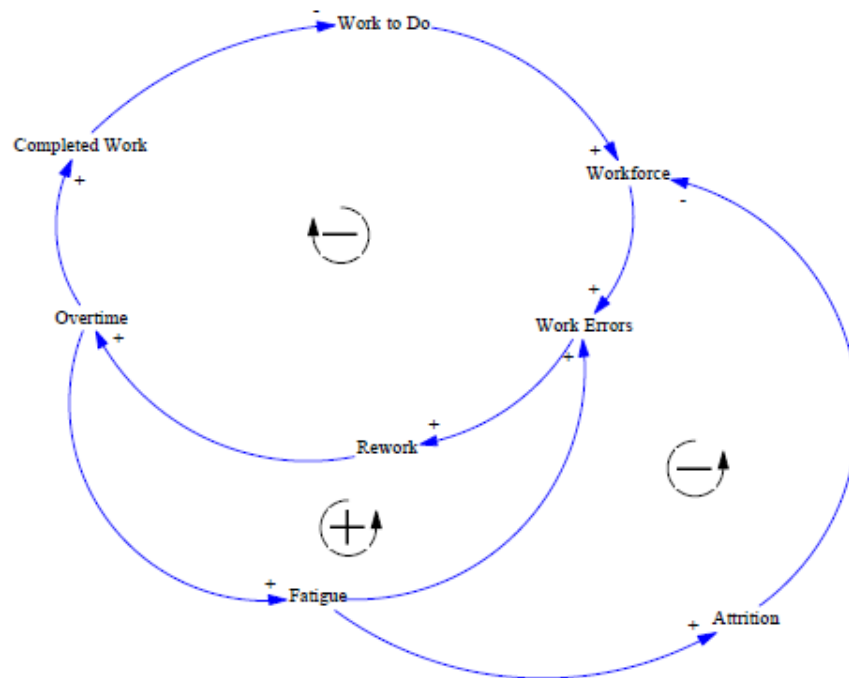


Figure 23: Attrition Causal Loop (adapted from Herweg and Pilon, 2001)

2. Trost (2002) measured fatigue when workload increases. Increased level of fatigue and schedule pressure both decrease the output of quality work. Meanwhile, training improves the worker's expertise and increases output quality of work. Sterman (2000) clarified that the fatigue, overtime, schedule pressure and rework loops are traditional system dynamics process elements. Figure 24 shows the detail of the loops among these factors.

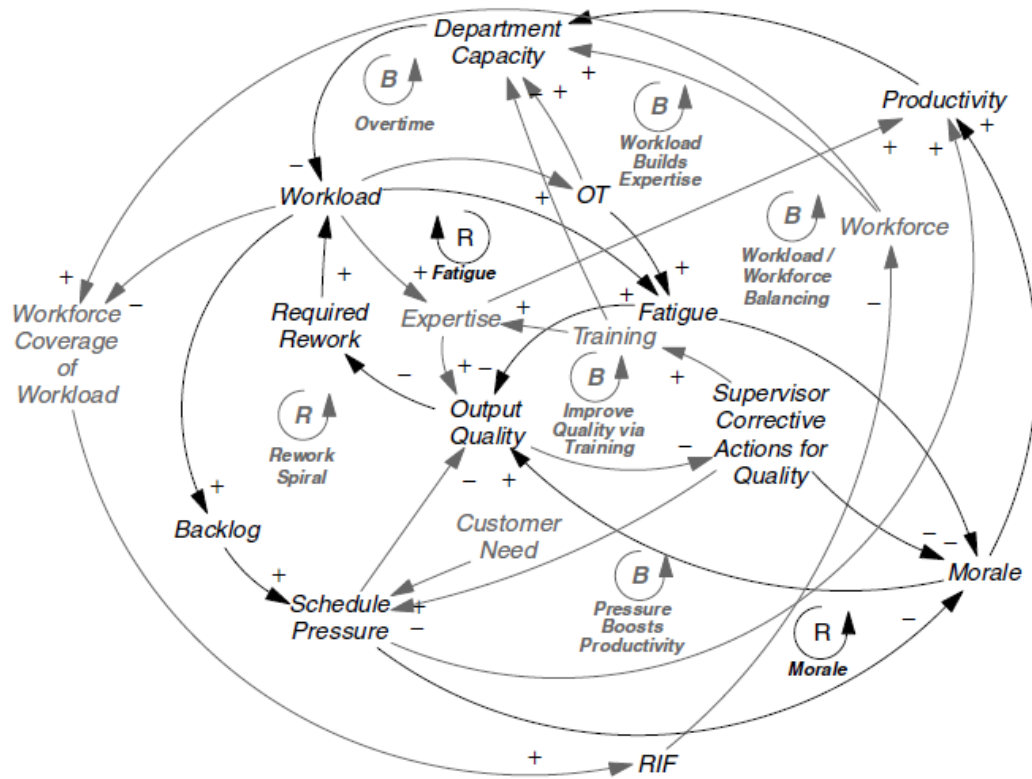
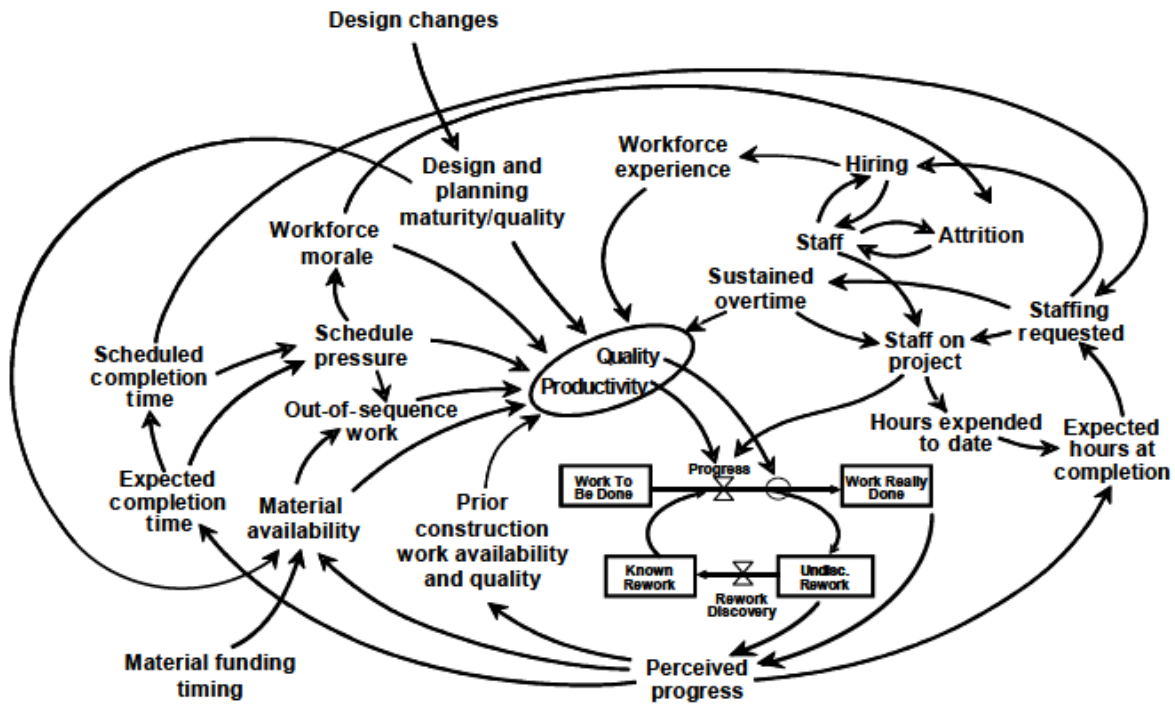


Figure 24: Fatigue and workload loop (adapted from Trost, 2002)

3. Johnson et al. (2009) also used System Dynamics modeling to build relationship for quality and productivity by using workforce morale, workforce experience, and schedule pressure.





training is needed to fill in the capacity gap and measure the number employees who are to be trained.

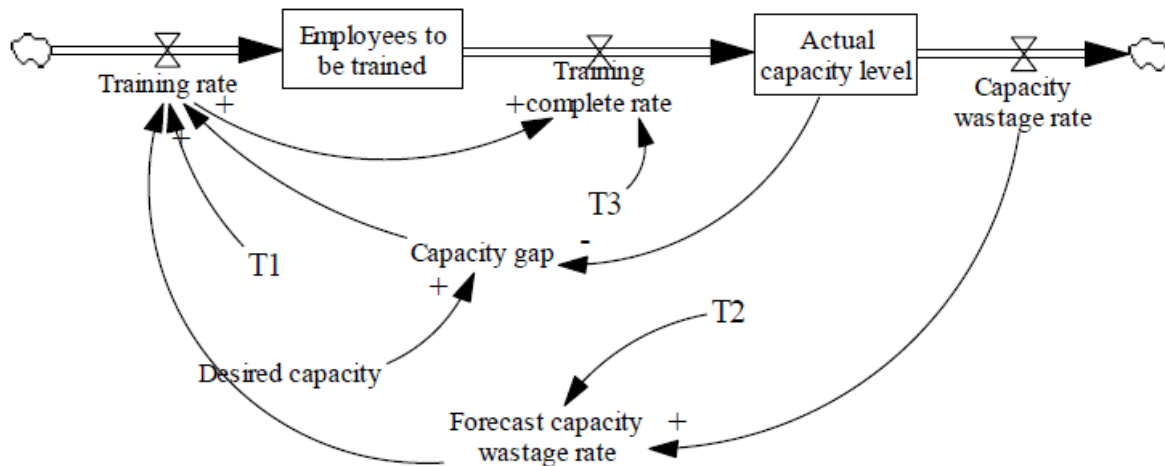


Figure 26: Stock and Flow Diagram of Human Resource Management (adapted from Gu and Chen, 2010)

2. Herweg and Pilon (2001) explored manpower planning in a project. They divided workers into three types of skill levels including novice, intermediate, and expert. Each phase within the project lifecycle utilizes a different combination of workers at these three skill levels. Figure 27 shows the number for these three types of workers can be adjusted by hiring, retiring, and attrition. Han (1997) also published research on workforce planning. Project managers take control of allocating project resources, such as manpower, facilitates, and equipment. In order to accomplish those tasks, they decide who to hire, who to train, and how to motivate employees to get the maximum effective work week. Figure 28 shows the relevant variables related to the number of employees in a project.

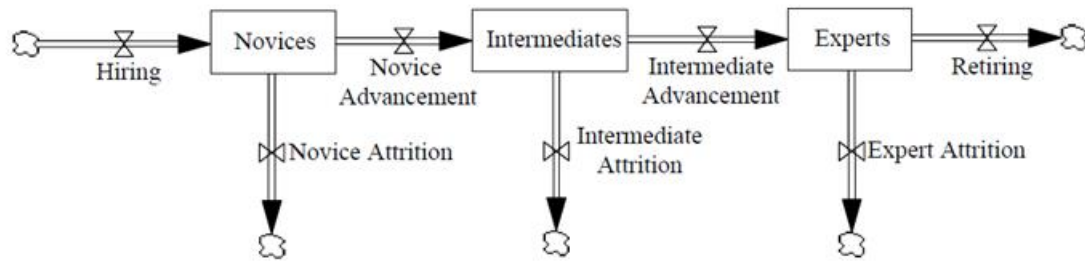


Figure 27: Workforce Skill Advancement Model (adapted from Herweg and Pilon, 2001)

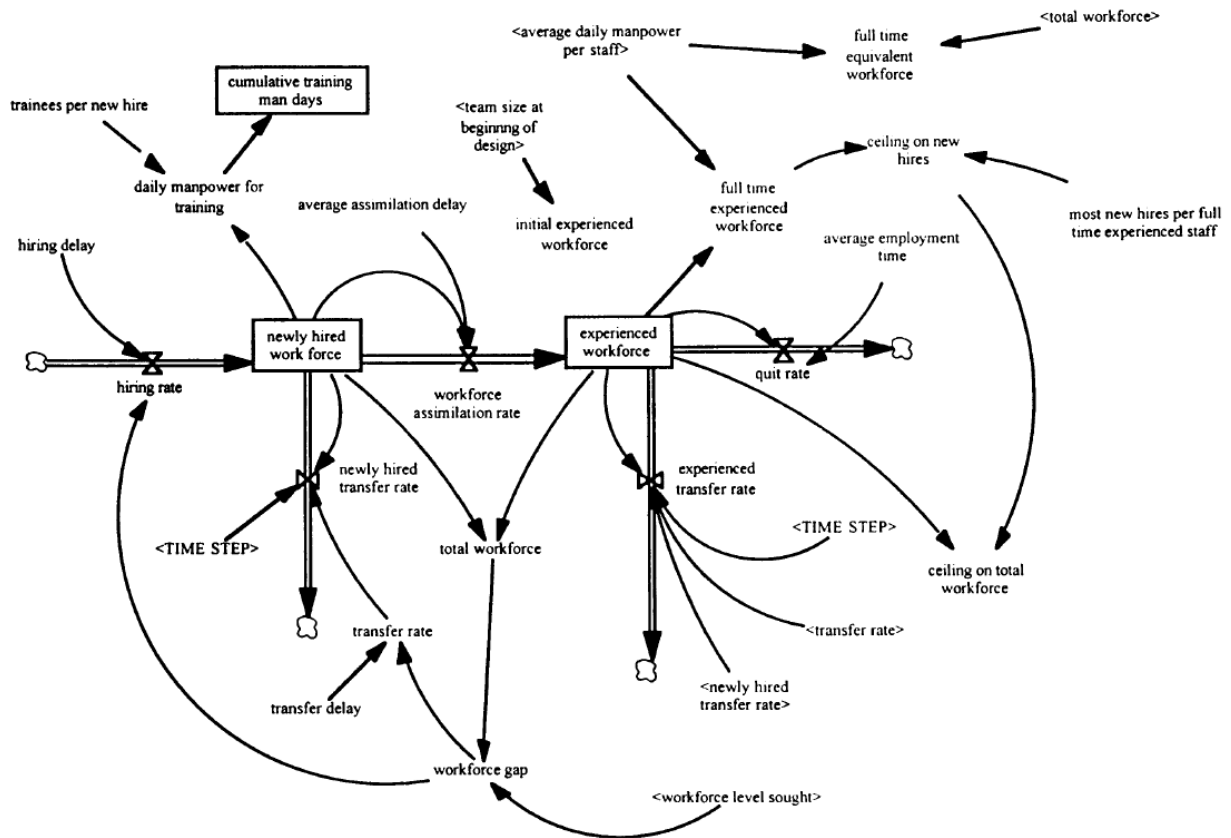


Figure 28: Workforce Planning Modeling (adapted from Han, 1997)

3. Lyneis and Ford (2001) published a study on project management using system dynamics modeling. One of the most successful applications is in the field of project management. The aim of project management is to find the qualified personnel at the minimum cost. Many have completed research projects in management related to human resources management. Figure 29 illustrates these three managerial actions which include add more people, work more and work faster in order to meet with the required project schedule. These loops include “Add People”, “Work More”, and “Work Faster/Slack Off” separately.

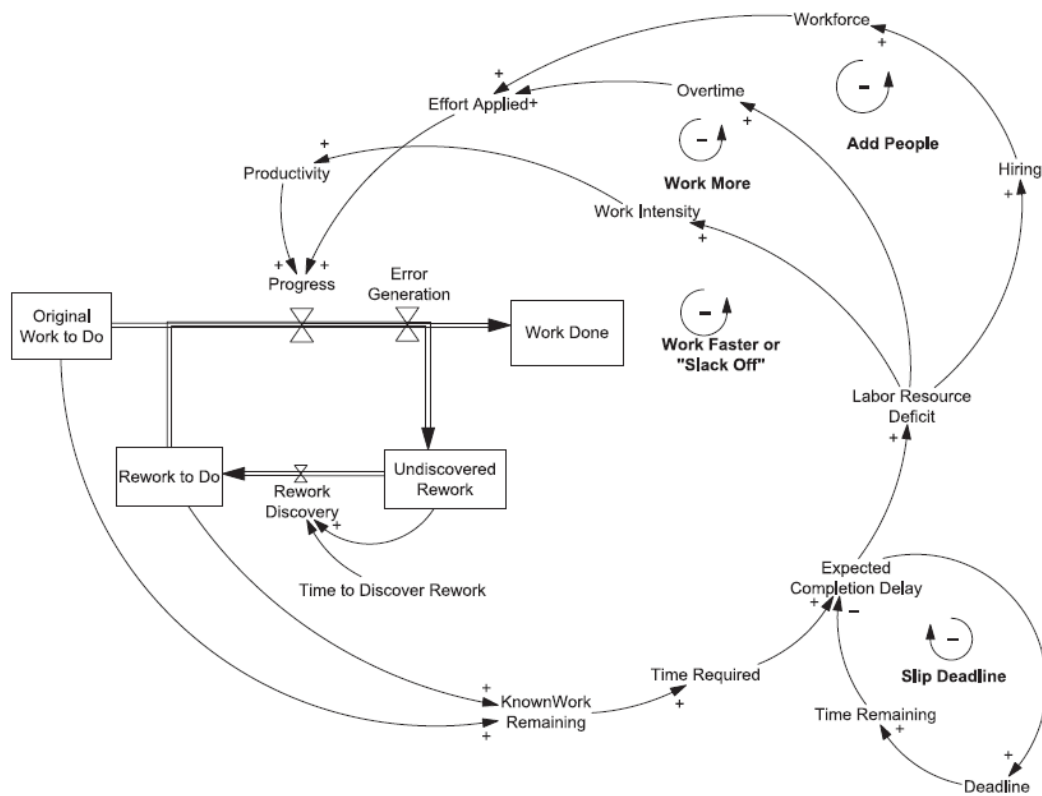


Figure 29: Actions of meeting project schedule (adapted from Lyneis and Ford, 2001)

In the same paper, Lyneis and Ford (2001) also illustrated that fatigue occurs when working overtime and leads to decreased productivity. Overtime has the potential of increasing errors and

reducing productivity. The amount of work remaining can be achieved by productivity and rework. Figure 30 shows the relationships between overtime and human performance factors.

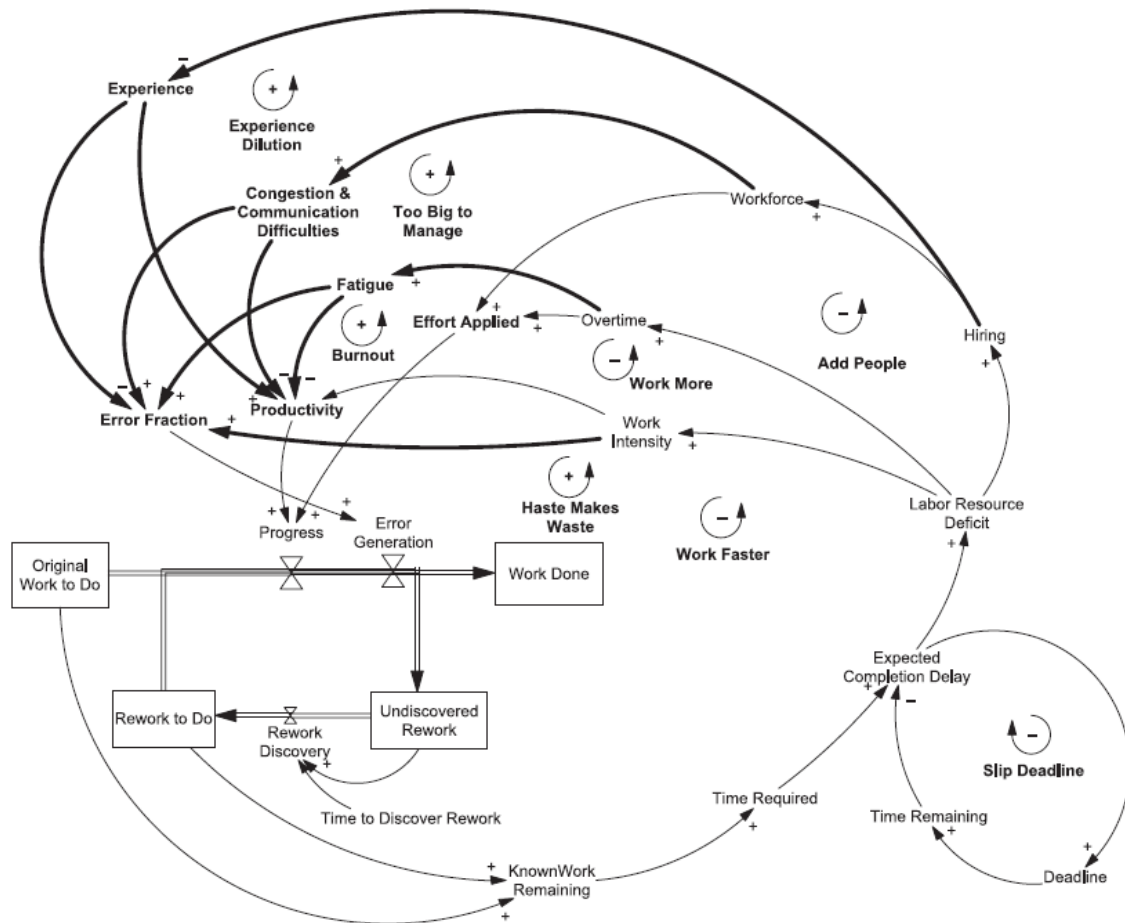


Figure 30: Human Performance with Workforce (adapted from Lyneis and Ford, 2001)

4. Cooper and Lee (2009) also illustrated System Dynamics modeling to aid project management at Fluor Corporation. Productivity reduction occurs when people become fatigued from working overtime and new employees who have less experience (Cooper and Lee, 2009). They measured project performance through project changes, rework, schedule pressure and workforce planning management. Many aspects of the project management structure affect the

productivity and quality as well as the hiring and turnover dynamics that affect the project's performance. Figure 31 reflected the perceived process has been considered to be lagging actual progress due to the rework cycle and the impact of hiring and overtime policies.

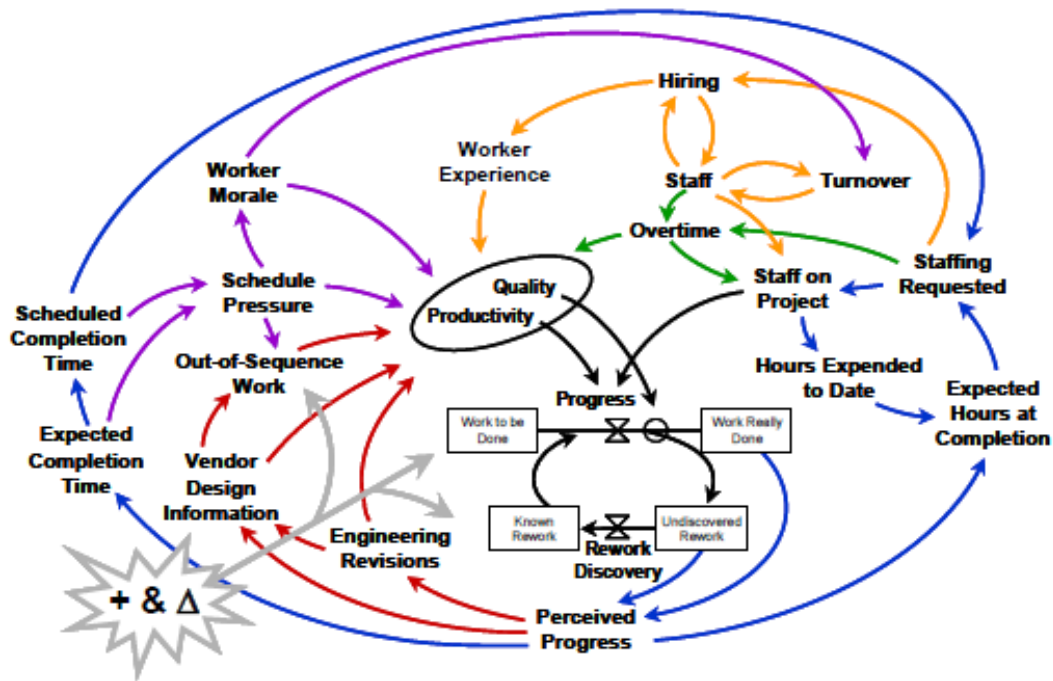


Figure 31: Project Dynamics with workforce, productivity, and rework (adapted from Cooper and Lee, 2009)

5. McCue (1997) accomplished research regarding project management in the shipbuilding industry. In his thesis, McCue (1997) used the SDM method to better understand the project's problems from hiring and firing policy cost estimating and overtime work. Figure 32 reflects the detail of the important variables which include the available workforce, project labor, planning work remaining and desired labor.

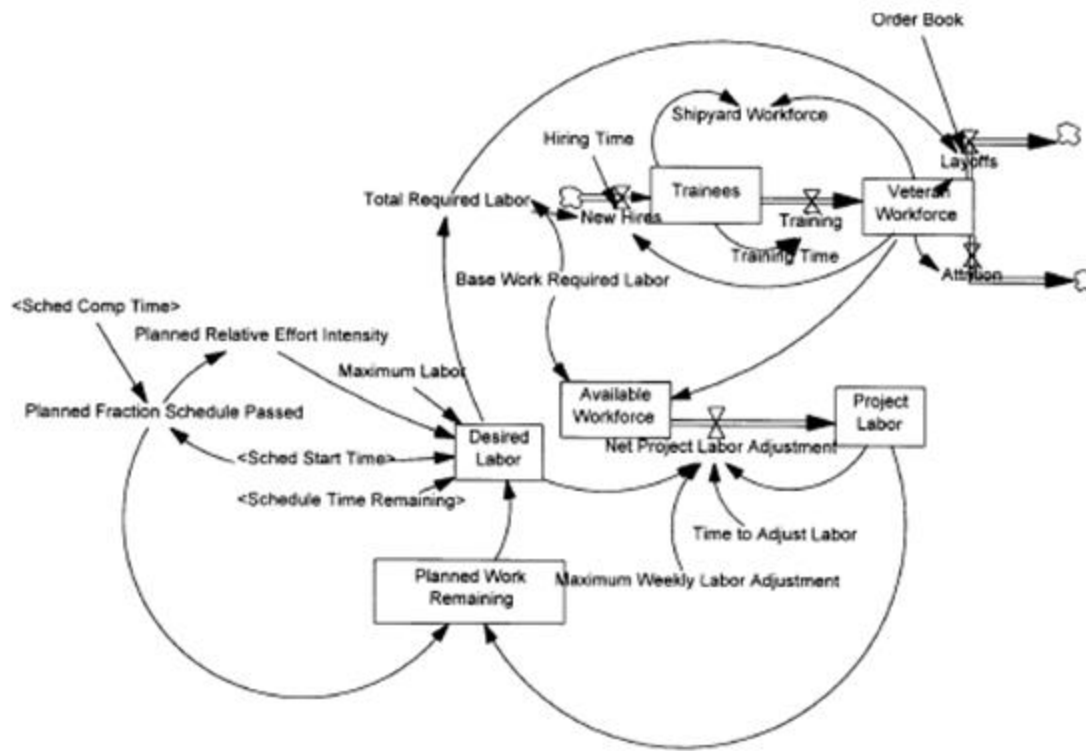


Figure 32: Labor Determination for Shipbuilding Industry (adapted from McCue, 1997)

6. An et al. (2007) published a workforce study by using System Dynamics modeling. One portion of the model includes a demand side which calculates how many workers the specific project needs. Another portion of the model includes a supply side which calculates how many skills in the labor market are needed to support the project. By simplifying workforce planning into supply chain management, workforce planning can be modeled more straightforwardly.

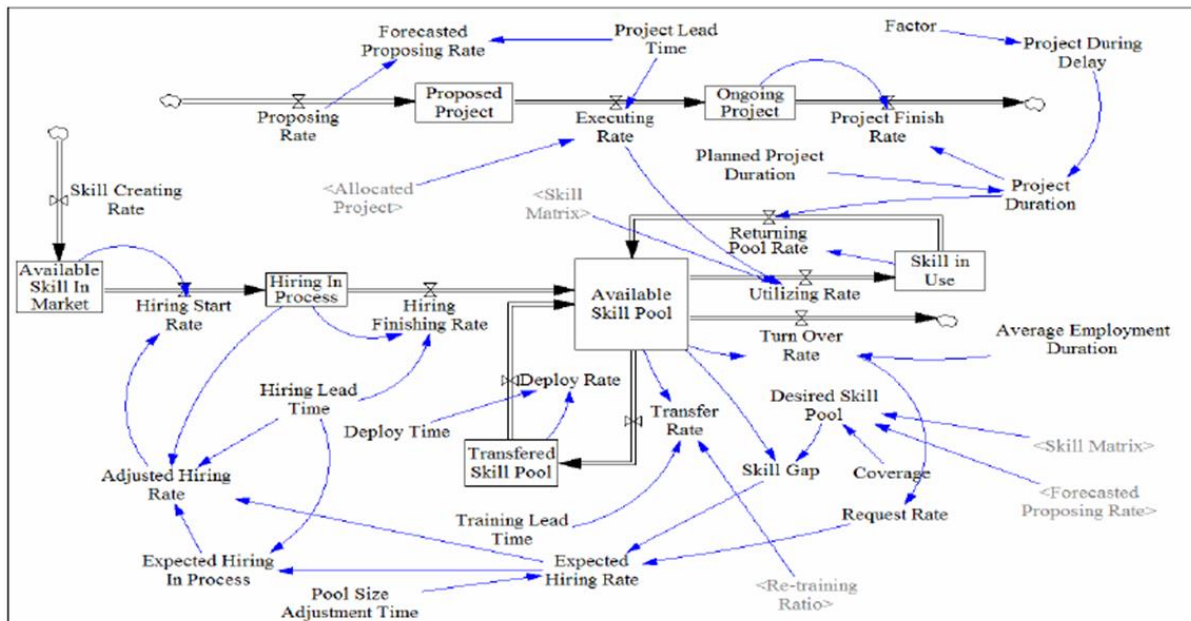
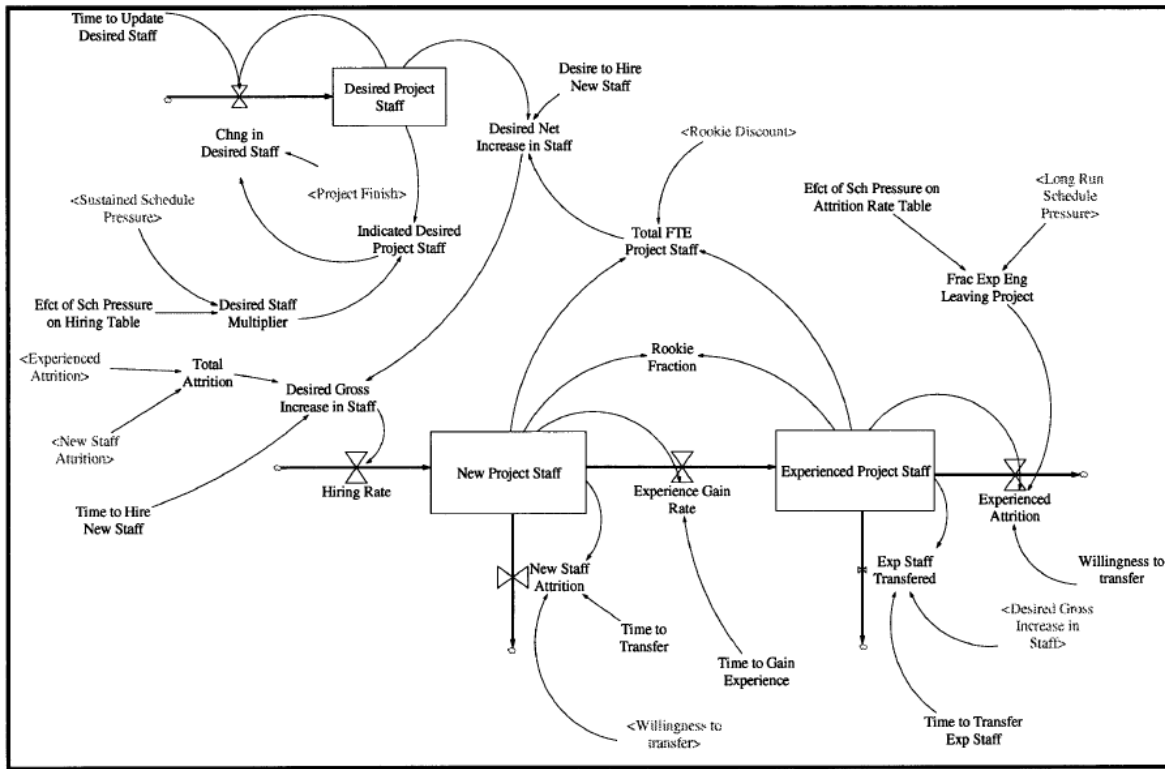


Figure 33: Workforce and Project Management (adapted from An and Ren, 2007)

7. MacInnis (2004) developed a system dynamics modeling for new product development.

Figure 34 depicted more details of his model.





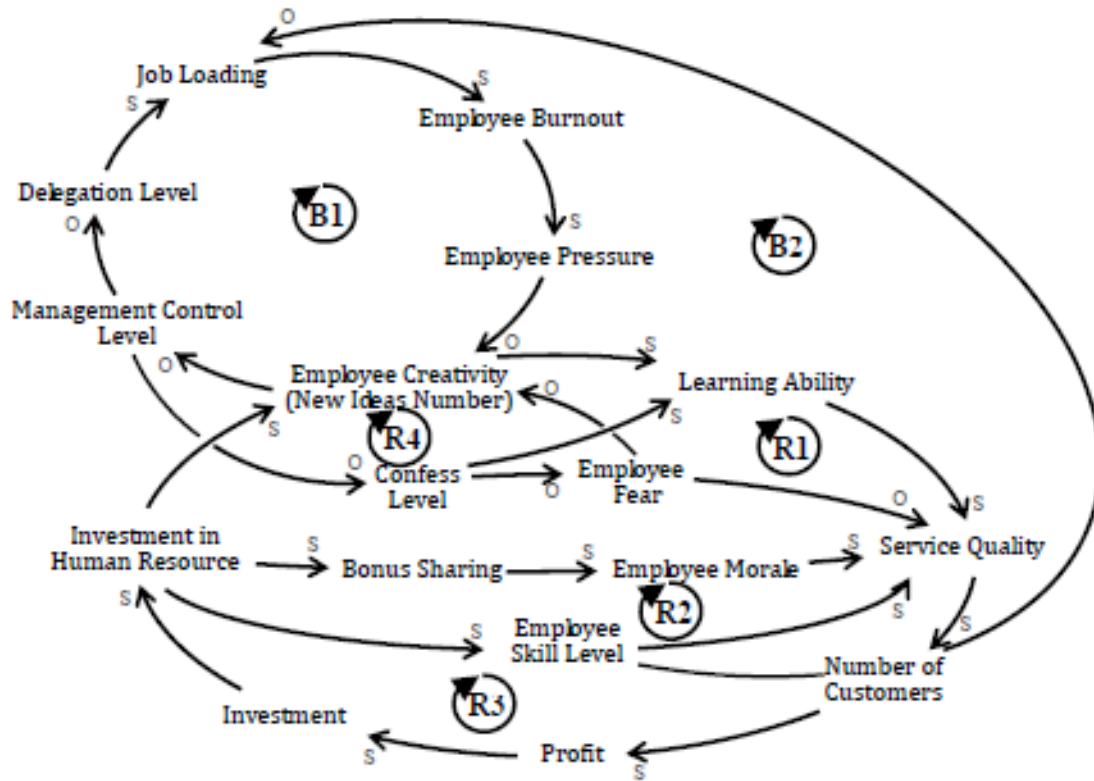


Figure 35: Human resource modeling for GE Company (adapted from Yang et al., 2010)

### 3.3.6 System Dynamics in Human System Integration

System dynamics modeling has the ability to model the performance and process of human system integration. Many researches have been made by using system dynamics modeling in human system integration application. The following section showed one example of applying technology to a new system.

#### 3.3.6.1 Human System Integration application

Technology is a very important variable in a new system. SDM can be used to predict changes in performance when new technology is applied in systems.



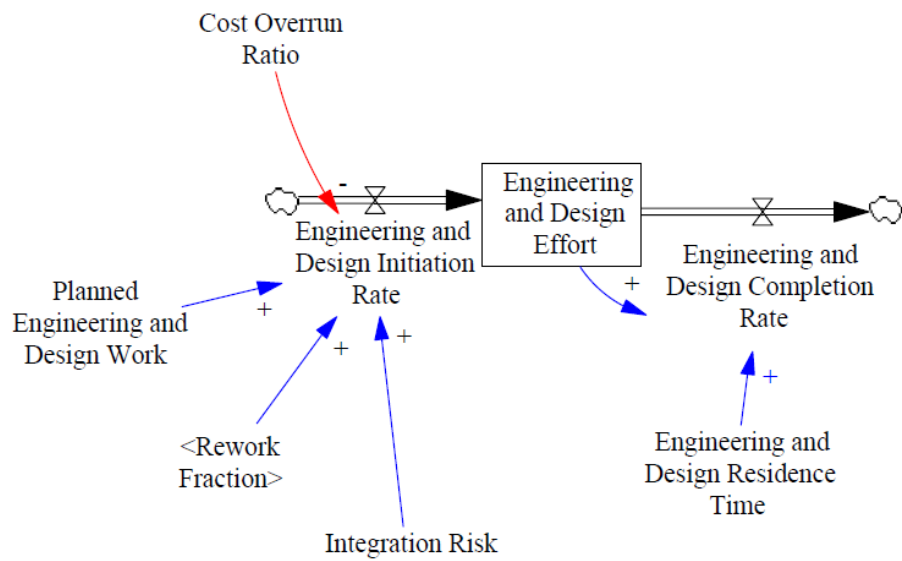


Figure 37: Engineering and Design Effort Structure (adapted from Damle, 2003)

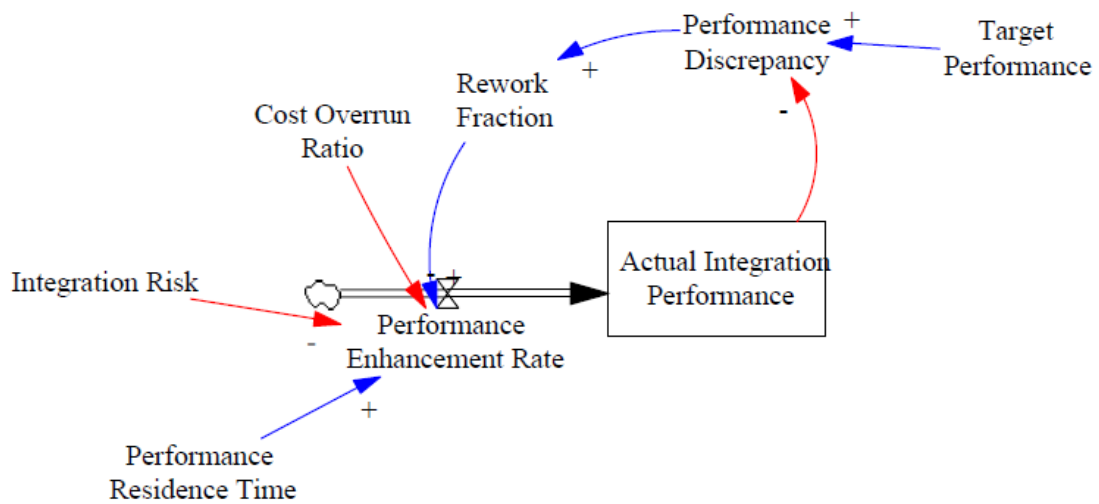


Figure 38: Performance loop (adapted Damle, 2003)

Madachy (1994) used ITHINK System dynamics modeling to complete analysis of manpower effort and rework relationship effort with cost software project development. He divided different manpower efforts and rework error effort during a software development process.

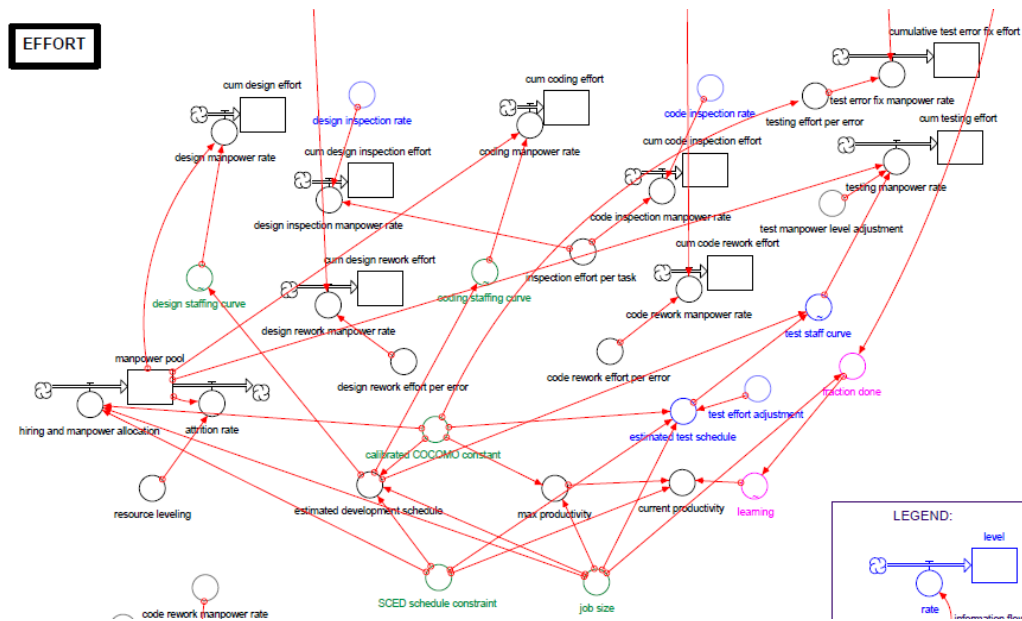


Figure 39: Manpower effort simulation (adapted from Madachy, 1994)

### 3.4 System Dynamics Software

There are four major software programs which have been developed for System Dynamics models. In addition, AnyLogic also supports applications in SDM. Eberlein's (2007) summarized that software as follows:

- DYNAMO: Dynamic Model was originally developed by Massachusetts Institute of Technology (MIT). It is considered as the first SDM language.
- Powersim ([www.powersim.com](http://www.powersim.com)): It was developed by the Norwegian government in the mid-1980s. It was also facilitated in interactive games or learning environments.
- Vensim ([www.vensim.com](http://www.vensim.com)): It was initiated in the mid-1980s and was commercially available in 1992. Currently it is widely used in the project development and analysis.
- iThink /STELLA (Structural Thinking Experimental Learning Laboratory with Animation) ([www.iseesystems.com](http://www.iseesystems.com)): It provided a graphical user interface for developing the SDM. It also widely used in the System Thinking and project development.
- AnyLogic: It provides supports various simulations such as discrete event simulation, system dynamics, and agent-based modeling.
- Simgua (<http://simgua.com>): Built to simulate and model complex systems. Simgua attempts to manage complexity of systems (Simgua website, 2012).

### 3.5 System Dynamics Modeling Process

Sterman (2000) described SDM processes and steps when dealing with the system dynamics modeling.

1. Define the problem---it is critical to define the system problem as clearly as possible to clarify important factors. Various important variables should be identified in this stage. A

system dynamics begins to consider a subsystem which is able to provide enough insight of a larger problem.

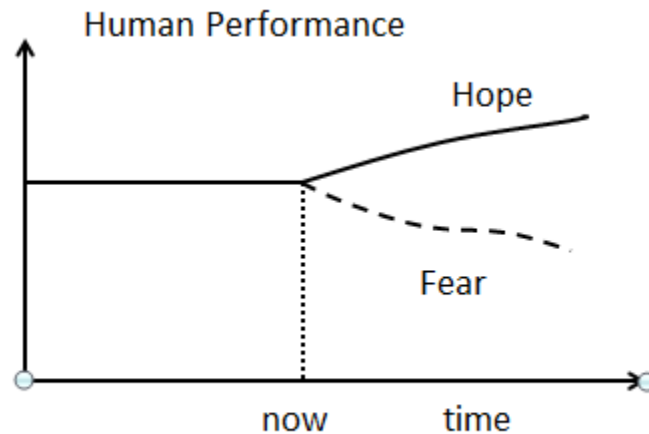


Figure 40: Reference mode of human performance

2. Determining the important variables: ---- a reference mode shows how the important variables are expected to change over time. Figure 40 depicts that the expected behaviors for human performance. The important variables are the key variables whose performance the model seeks to improve. These selected variables should capture the important dynamics of the model while also demonstrating other important inherent behaviors (Bakkila, 1996).
3. Developing a dynamic hypothesis----- as the figure shows above, the underlying hypothesis is as more training time is invested, better human performance will be earned.
4. Developing a causal loop diagram---- a causal loop diagram (CLD) is used to map the cause-effect relationship between different variables within the system. The two variables

are linked with an arrow with one of the two states of polarity, positive (+) or negative (-). For example, as the training time increases, human performance also increases.

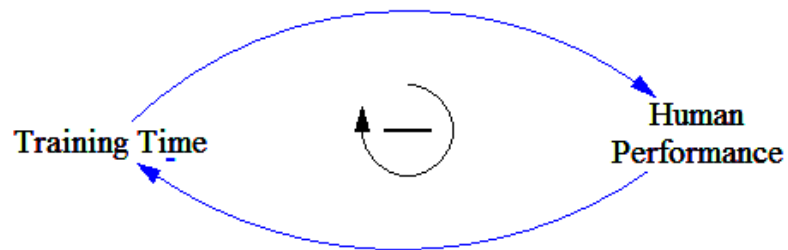


Figure 41: Negative Causal Loop: Training Time and Human Performance

5. Testing and validation --- model should be tested for robustness. Extreme conditions need to apply in the model to robust model behaviors.

Andersen and Richardson (1980) described six steps in SDM process. The “conceptual” steps include Problem Recognition, System Conceptualization, and Model Representation. The “technical” steps include Model Behavior, Model Evaluation, and Model Use. They are described in Figure 42 below:

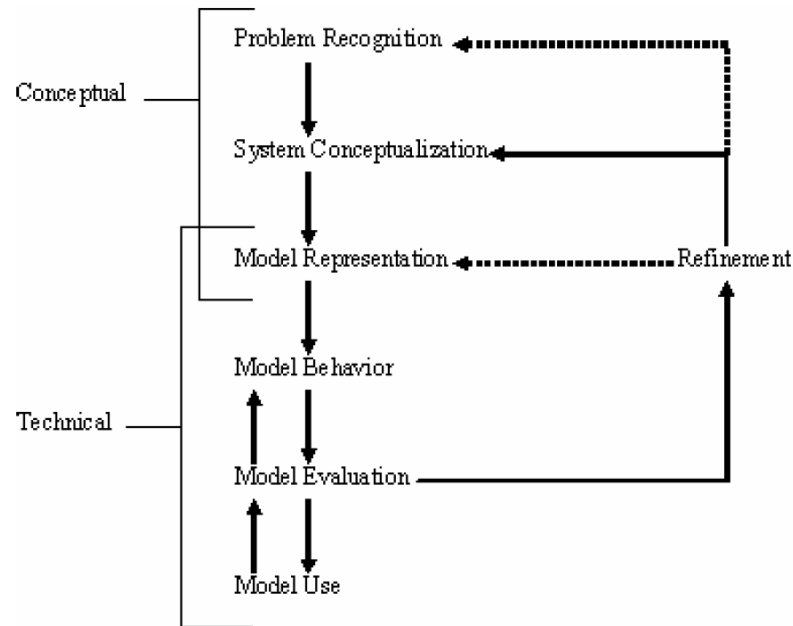


Figure 42: System Dynamics Modeling Steps (adapted from Richardson and Anderson, 1980)

### 3.6 System Dynamics Model Behaviors

There are three different fundamental behaviors in the SDM. The dynamic behaviors are generated due to different feedbacks within the system. Exponential growth, goal seeking, and oscillation are the fundamental behaviors (Sterman, 2000). These are defined below:

**Exponential Growth:** It is defined as when the change in one quantity within the system causes a change in the positive direction of the other. This self-reinforcing feedback occurs due to positive behavior. In other words, a change in the first quantity causes a positive effect that reinforces the positive effect in the other.



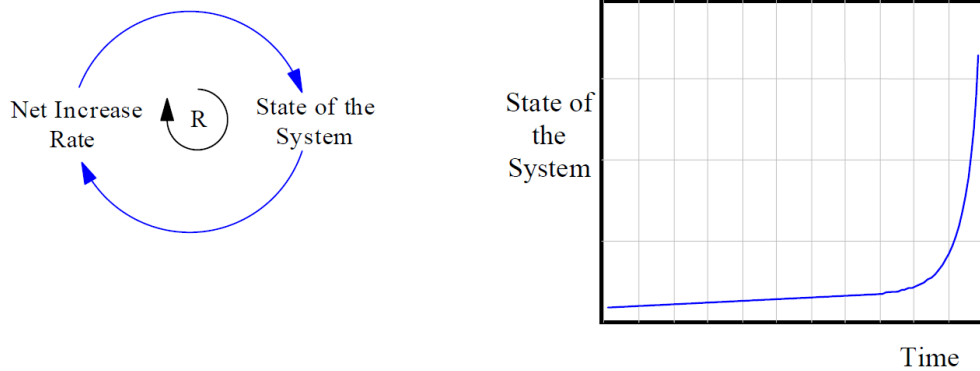


Figure 43: Exponential Growth (adapted from Sterman, 2000)

**Goal Seeking:** It is defined as by a self-balancing loop. When this occurs corrective actions take place when the discrepancies increase. Goal seeking occurs when the system moves toward the overall desired state and corrective action is taken toward the goal.

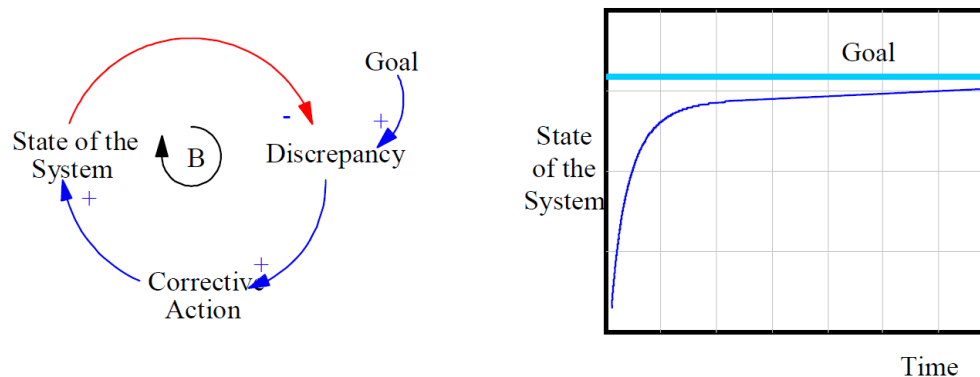


Figure 44: Goal Seeking (adapted from Sterman, 2000)

**Oscillation:** It is occurred when there is a delay in the negative feedback loop and the system over shoots the goal and then corrects in the opposite direction. Oscillation is similar to goal seeking except for the delay and the fact that the system does not reach the goal as quickly. This is caused by the fact that the negative feedback loop must move the system over and over as each correction results in overshooting the goal again and again.

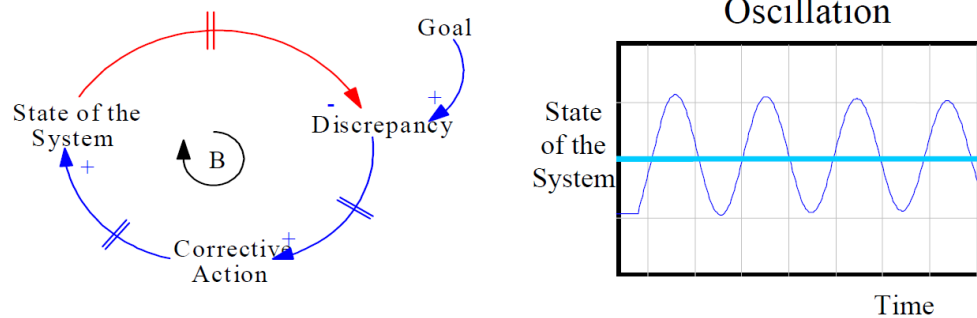


Figure 45: Oscillation (adapted from Sterman, 2000)

### 3.7 Conclusion

System Dynamics has been used in many fields since it was developed in the 1950s. It has been applied in applications such as business performance, organizational performance, financial, cost reduction, marketing development, and supply chain management. This chapter gave us an overall review of the System Dynamics modeling application and then focuses on applications focusing on the System performance, human performance, human factors and human system integration.

System or organizational performance can be achieved by each worker's effort within a team. System performance cannot be separated from operators or workers' effort and contribution in an organization. Human performance can be measured by human liability, stress, fatigue, cognitive load and work load based on the previous research. In addition, this chapter also reviewed System dynamics modeling applications in human system integration. The fields of human factor

engineering, personnel and training are included in human system integration. For many years human system integration and system dynamics modeling have been used together to understand the complex processes and changes introduced by new technology in systems.

### 3.8 Research Gap

Based on two literature reviews, a research gap had been discovered. The following table shows the detail of the research gap.

Table 6 Research gap

| Study   | Aspect                             |                      |                                       |                                 |                          |                    |           |          |
|---|------------------------------------|----------------------|---------------------------------------|---------------------------------|--------------------------|--------------------|-----------|----------|
|   | System/Organization<br>performance | Human<br>performance | Stress,<br>workload<br>and<br>Fatigue | Human<br>Resource<br>Management | Human System Integration |                    |           |          |
|   |                                    |                      |                                       |                                 | Technology               | Manpower<br>effort | Tradeoffs | Training |
| Morrison ( 2007); Repenning and<br>Sternman (2002);Prasertrungruang<br>and Hadikusumo<br>(2008);Bajracharya et al, (2000)         | x                                  |                      |                                       | x                               | x                        |                    |           | x        |
| Chu, 2010 ;Wang and Tu(2012) ;<br>Yu et al. (2004) ;  |                                    | x                    | x                                     |                                 |                          | x                  |           | x        |
| Woods and Dekker (2000); Morris,<br>Ross and Ulieru (2010) ; Herweg<br>and Pilon (2001) ; Trost<br>(2002) ;Johnson et al., (2009) |                                    | x                    | x                                     | x                               |                          | x                  |           |          |

| Study  | Aspect                             |                      |                                       |                                 |                          |                    |           |          |
|--|------------------------------------|----------------------|---------------------------------------|---------------------------------|--------------------------|--------------------|-----------|----------|
|  | System/Organization<br>performance | Human<br>performance | Stress,<br>workload<br>and<br>Fatigue | Human<br>Resource<br>Management | Human System Integration |                    |           |          |
|  |                                    |                      |                                       |                                 | Technology               | Manpower<br>effort | Tradeoffs | Training |
| Damle (2003)   |                                    | x                    |                                       | x                               | x                        | x                  | x         |          |
| Madachy (1994)   |                                    | x                    |                                       | x                               | x                        |                    |           |          |
| Lizza et al(2008) ; Booher (1997,<br>2003);Bost and Galdorisi<br>(2004) ;Scofiled (2006) ;Spindel et<br>al (2000) ;          | x                                  | x                    |                                       | x                               |                          |                    | x         |          |
| Koopeman and Golding<br>(1999) ;Osga and Galdorisi (2003);<br>Correno et al (2010) ;Thie<br>(2008);Bost and Galdorisi (2004) | x                                  | x                    |                                       |                                 | x                        |                    | x         |          |

| Study                                     | Aspect                             |                      |                                       |                                 |                          |                    |           |          |
|---|------------------------------------|----------------------|---------------------------------------|---------------------------------|--------------------------|--------------------|-----------|----------|
|   | System/Organization<br>performance | Human<br>performance | Stress,<br>workload<br>and<br>Fatigue | Human<br>Resource<br>Management | Human System Integration |                    |           |          |
|   |                                    |                      |                                       |                                 | Technology               | Manpower<br>effort | Tradeoffs | Training |
| Scofield (2006) ;Douangaphavong<br>(2004) |                                    |                      | x                                     | x                               |                          | x                  | x         |          |
| Booher (2003)                             |                                    | x                    |                                       |                                 |                          | x                  | x         | x        |
| Simpson (1995)                            |                                    | x                    |                                       | x                               |                          |                    |           | x        |
| Jiang (2013)                              | x                                  | x                    | x                                     | x                               | x                        | x                  | x         | x        |

## **CHAPTER FOUR: METHODOLOGY**

### **4.1 Proposed Methodology**

Based on the research questions and objectives, a methodology was constructed in order to build a system dynamics model. The methodology for this particular research was directed by a System Dynamics Modeling (SDM) approach. Chapter Three summarized SDM applications which had been used to describe, generate and test a series of hypotheses about the behavior of complex systems. Major steps in this research processes are as follows:

Step 1: Review the current budget issue of the Navy

Step2: Literature review of manpower cost methods

Step 3: Literature review of System Dynamics Modeling approach in human related factors

Step 4: Define new technology by key terms: as new technologies are introduced to the system, key variables need to be defined to describe these new technologies. Table 7 defines technology by these key variables

Step 5: Build causal loop diagrams and discuss with Subject Matter Experts (SME) from the Navy. In order to generate the dynamics observed in the literature a process is created that explains how the variables interact. The key causalities come from literatures and recent publications. The causalities were reviewed by SMEs who understand operations of the naval combatant ships

Step 6: Build Stocks and Flows diagrams to estimate manpower cost associated with new technology implementation. This process includes sensitivity analysis and What-if analysis for different cases

Step 7: Compare different technology implementation and evaluate the difference of the manpower cost associated with different implementation periods

The following figure shows the model architecture by defining major variables.

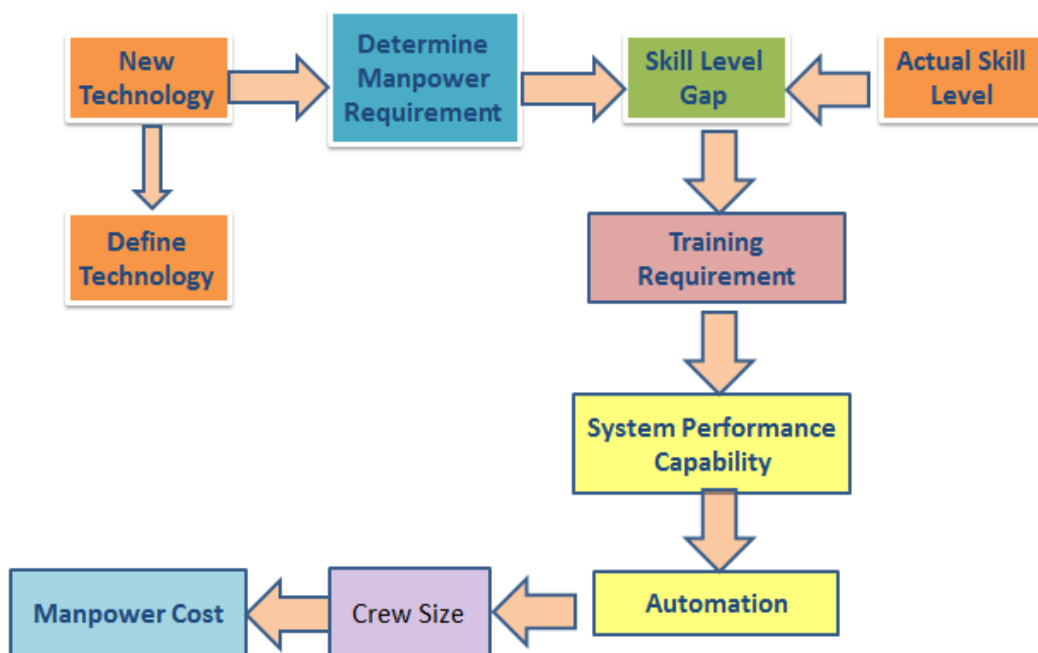


Figure 46: Major variables for manpower cost estimation



#### 4.2 Sector Map

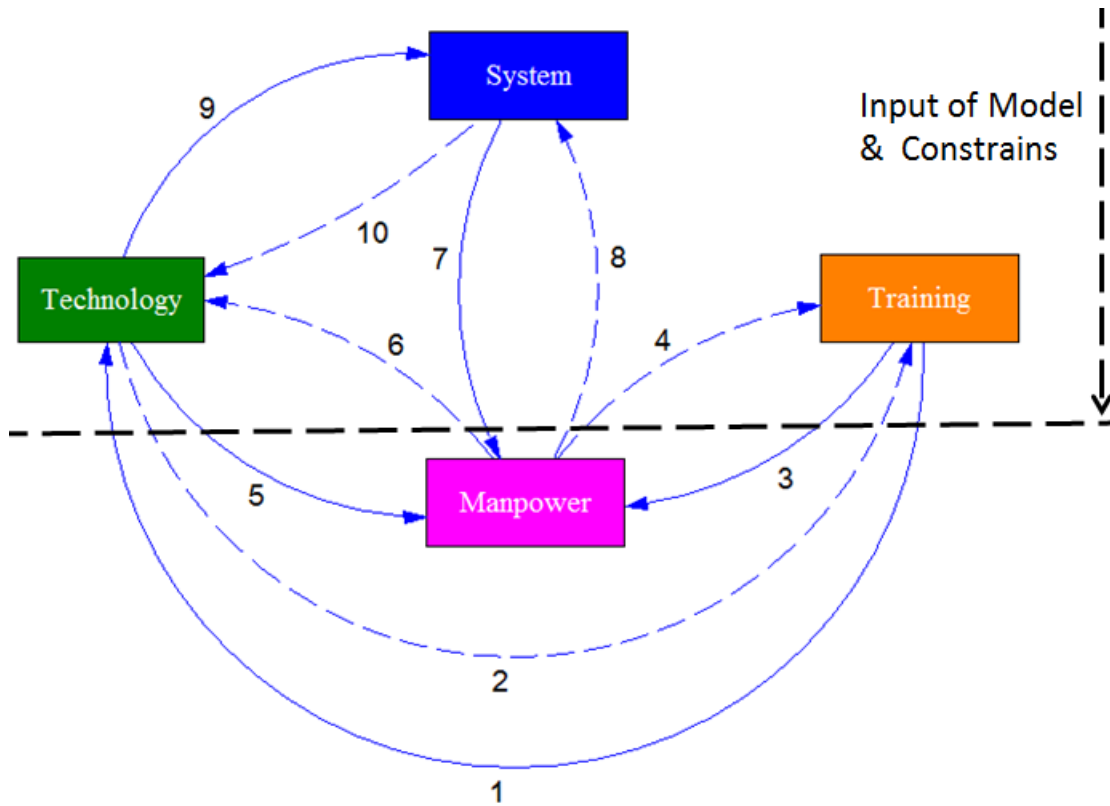


Figure 47: Sector map

There are four sectors in this model. Each sector has different key variables to define the model:

- System: includes system capability
- Manpower: includes manning skill level and Crew size
- Training: includes training cost and training technology
- Technology: includes technology implementation and technology complexity

These four sectors have been considered in this model. The major sector for this study is the manpower sector. However, manpower sector could not be separated from other sectors. The following table describes this sector map of these ten effects in details.

Table 7 Effects in the four sections

| Effect number | Name                   | Description   |
|---------------|------------------------|---|
| Effect 1      | Training to Technology | Cost of training for specified Technology   |
| Effect 2      | Technology to Training | Training requirement specify Technology skill                                     |
| Effect 3      | Training to Manpower   | Training increases Manpower size and skills                                       |
| Effect 4      | Manpower to Training   | Manpower specifies Training requirement   |
| Effect 5      | Technology to Manpower | Technology specifies Manpower requirement   |
| Effect 6      | Manpower to Technology | Manpower constrains Technology selection  |
| Effect 7      | System to Manpower     | System affects Manpower in terms of stress, fatigue, safety and habitability      |
| Effect 8      | Manpower to System     | Manpower affects System effectiveness and efficiency                              |
| Effect 9      | Technology to System   | Technology improves System capability   |
| Effect 10     | System to Technology   | System constraints type of Technology in terms of compatibility and affordability |

In these effects, effect 3, 4, 5, 6, 7, and 8 are major effects for manpower considered in this model.

### 4.3 Causal Loop diagram

Building Causal Loop diagrams (CLD) is one of major steps in this research. The goal of building CLD is to create a comprehensive understanding of how the variables interact with manpower cost in order to generate the dynamics observed in the literature.

Since this research specifies the trade-off space between manpower and technology implementation. Figure 48 describes that manpower gap will generate between manpower supply and manpower demand when implementing new technology. However, training has the ability to fill this gap. When training is administered to sailors, it helps decrease the gaps required for manpower skill. The pressure increases for program managers when the training cost is increased because of the increased training duration. Therefore, choosing efficient training technology is imperative for program managers. The following figure describes when new technology is implemented into the system, extra training is needed to fill up the manpower gap.

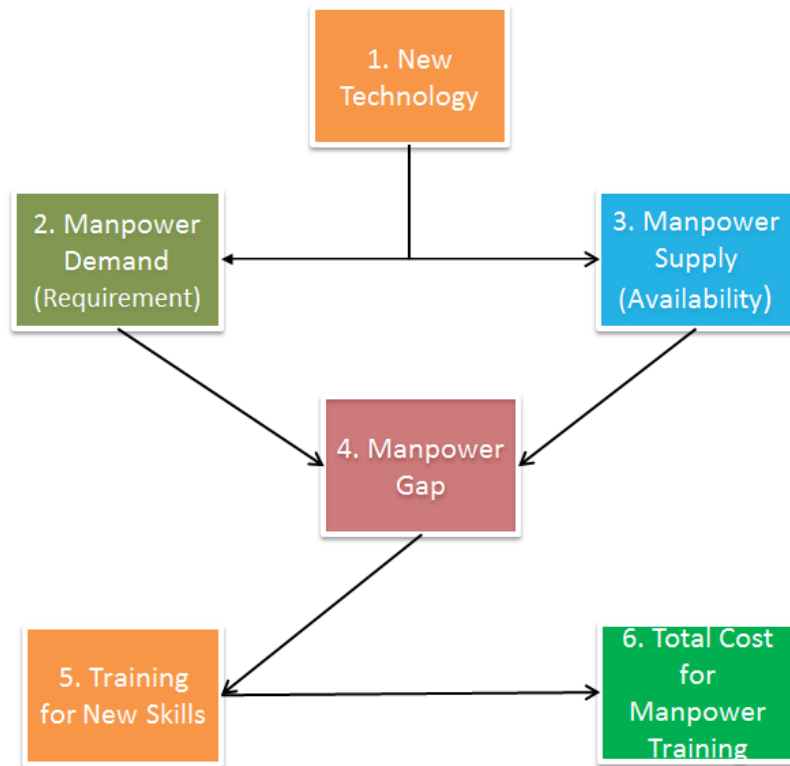


Figure 48: Training for filling up the Manpower requirement gap

#### 4.4 Model structure

The goal of model structure is to illustrate key sections of the SDM. In this model, there are four sub-systems including manpower, technology, training and system. Each subsystem comprises various variables, which is constructed to their corresponding relationship in the model.

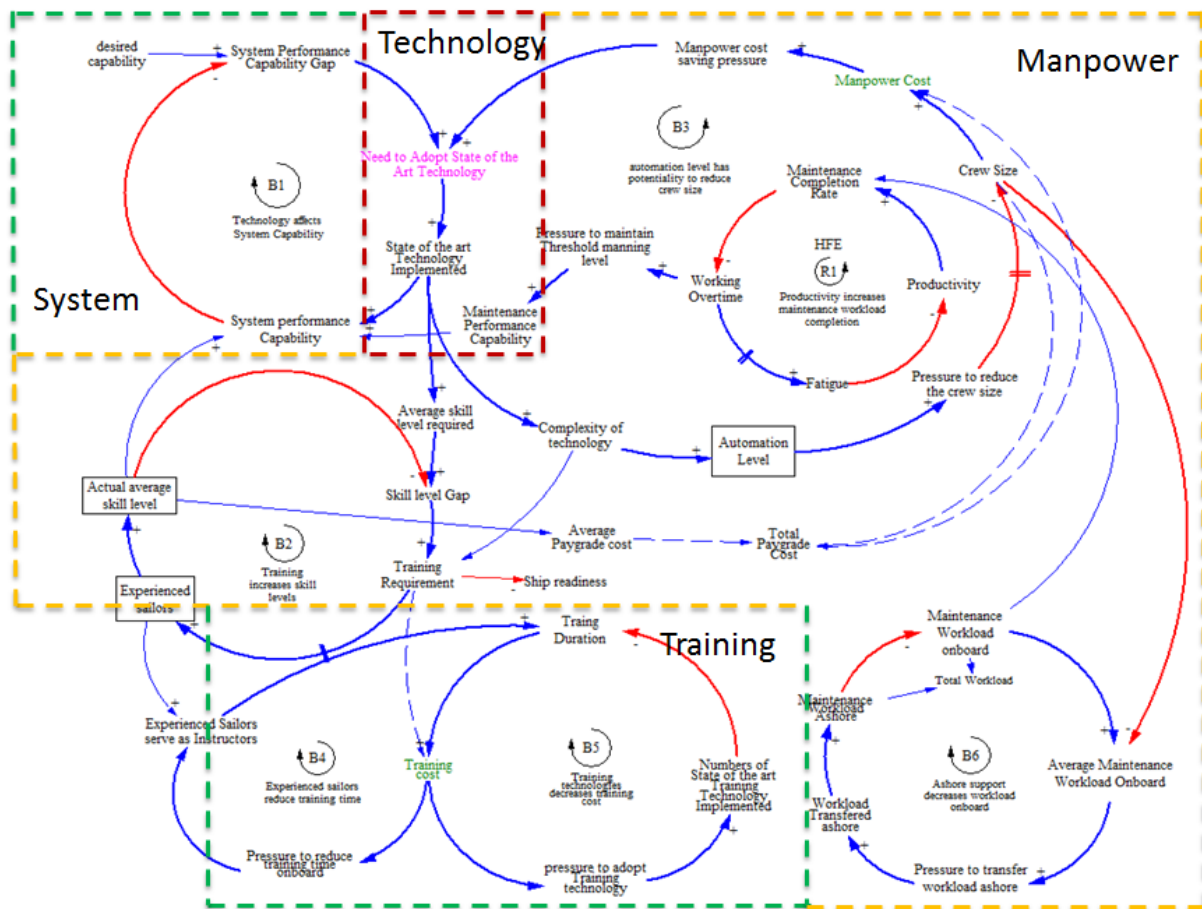


Figure 49: Four sections in the Casual Loop diagram

Figure 49 depicts the CLD in four sections including system, technology, manpower and training. This diagram was also listed in the Appendix A. Chapter Five describes this diagram in details.

#### 4.5 Defining technology

Since technology is the input for the SDM, it is important to define technology. Technologies can be defined by the following key variables.

Table 8 Technology Defining by Key Variables

| Key Factors         | Defining  |
|---------------------|---|
| Level of complexity | How complex the new technology is                                       |
| Implementation rate | How often to implement the state-of-the-art technology                  |
| Automation level    | The level of automation in the system                                   |
| Reliability         | The ability of technology to consistently perform its intended function |
| Upgradability       | How easily be upgraded into a system                                    |
| Lifespan            | The period of technology keeps its functions                            |
| Maturity            | Degree of fully developed   |
| Safety              | Condition level unlikely to cause danger, risk or injury to sailors     |
| Compatibility       | Capable of performing in harmonious with other system                   |
| Affordability       | Able to afford specific type of technology within the DoN budget        |

In this research, the level of complexity, automation level, and technology implementation rate were considered in the model. Future study needs to consider the rest of key variables of technology for modeling process.

#### 4.5.1 New Technology affect Manpower

The Navy continues to implement new technologies for existing and new ship system. Electric drive technology is a good example of implementing new technology which has the effect on manpower and ship system.

Electric drive technology has many benefits in reducing cost, noise and maintenance requirement (Doerry, 2010). This type of technology will open immense opportunities of manpower reduction and improvement of shipboard life.

#### 4.5.2 Data Source and Model Guidelines

In this research, specific data are needed to test model. The following data base and guidelines were used in the model processes and model testing.

- Department of the Navy Budget Materials
- Government Accountability Office (GAO)
- The Navy Manpower Analysis Center (NAVMAC)
- The Navy Manpower Requirement System (NMRS)
- Ship Manpower Document (SMD)

- Army Manpower Cost System (AMCOS)
- The Navy Center for Cost Analysis
- Department of Defense instructions and publications

With the data sources and guidelines, model can also be calibrated and validated. Chapter Six discusses the model testing and validation in details.

#### 4.6 Trade-off Space

Trade-off spaces include manpower and technology implementation, manpower and system capability, and manpower requirement and training cost. The Stocks and Flows diagrams in Chapter Five show the details of trade-off analysis between manpower and technology implementation.

Trade-off space between manpower and system capability is important when considering manpower impact on system capability. Risk and reliability need to be considered in the system capability. System performance such as reliability and maintainability also needs to be considered in the trade-off analysis. Reliability and maintainability are the most significant cost drivers for operating and supporting the Navy ship system (Clarke, 1990). These factors have impact on the manpower number and skill levels as well. For example, the system reliability determines the number of corrective maintenance, so does the number and skills of maintenance personnel.

The following table contrasts the two issues of system capability (e.g. readiness, reliability) and manpower cost. Decision makers make their choices by comparing different scenarios.



Table 9 Assessment of Different Trade-off Scenarios

| <b>System Capability (e.g. Readiness, Reliability, maintainability)</b> |           |             |                         |                    |
|---|-----------|-------------|-------------------------|--------------------|
|   |           | Increased   | Same                    | Decreased          |
| <b>Manpower Cost</b>  |           |             |                         |                    |
|   | Increased | Acceptable? | Undesirable             | Very Undesirable   |
|   | Same      | Acceptable  | Efficient Workforce?    | Undesirable        |
|   | Decreased | Nirvana     | Choose this technology? | Cutting workforce? |

Although the trade space between manpower and system capability is important, this model does not consider that in a very detail. Instead, this research explores trade space between manpower and technology implementation in details. Different technology implementation periods engender different impacts on manpower cost.

## CHAPTER FIVE: MODEL DEVELOPMENT

According to Sterman (2000), an effective model should follow mainly four steps:

1. Problem Articulation
2. Formulation of Dynamics Behaviors
3. A Simulation Model Formulation
4. Validation

### 5.1 Problem Articulation

It is important to clarify the purpose of the model. A clear purpose can prevent that modeling process from moving off track.

As defined in the objectives of this research, the System Dynamic Model (SDM) mainly captures:

1. Identify major factors which impact the Navy manpower cost within new technology implementation
2. Facilitate Navy manpower cost to better understand the impact for TOC
3. Provide the necessary information to investigate manpower cost and technology trade-off analysis
4. Examine different scenarios of HSI major factors (e.g. training, human factors engineering) effect on manpower cost drivers

### 5.1.1 Purpose of the Model

The purpose of the model can be summarized as follows:

1. To estimate manpower cost and technology tradeoff associated with different technology implementation
2. To assess crew size and manpower skill levels for a ship system
3. To estimate training cost for different training technologies and numbers of instructors

### 5.1.2 Assumptions of the model

In order to avoid modeling complexity, the assumptions need to be made.

1. System performance capability increases when implementing new technology.
2. New technology implementation can be substituted for crew. After implementing new technology in the system, automation level increases in the entire system.
3. Increased manpower cost saving pressure increases the pressure to adopt the state-of-the-art technology. Decision makers want to decrease manpower cost by adopting more advanced technologies.
4. The more complex a technology, the higher is the anticipated automation level of the system.

5. The higher the skill level gap of sailors, the higher requirement for training. Increased training requirement increases numbers of experienced sailors.
6. Increased state-of-the-art training technologies decrease training time.
7. Higher numbers of experienced sailors serving as instructors has a positive effect on decreasing training time.
8. The model considered the DDG-51 Arleigh Burke Class for its prototype and the base model parameters were built based on DDG-51 Class public data. For example, there are 300 enlisted sailors currently onboard.

### 5.1.3 Key Variables

There are several key variables in the model which also describe four sectors mentioned in the Chapter Four. These variables are defined in the following table.

Table 10 Definitions of Major Variables

| <b>Variables</b>                          | <b>Description</b>   | <b>Unit</b>   |
|---|--|---------------|
| Manpower cost<br>saving pressure          | Saving pressure due to the Navy budgeting cut.<br><br>Manpower cost is approximately 50 percent of TOC | Dimensionless |
| Need to Adopt state-of-the-art Technology | Potential to implement state-of-the-art Technology as manpower cost saving pressure increases          | Dimensionless |
| State-of-the-art Technology Implemented   | Advanced level for the state-of-the-art Technology   | Dimensionless |

| <b>Variables</b>                           | <b>Description</b>  | <b>Unit</b>   |
|--|---|---------------|
| Average skill level required               | Average skill level to operate system under the new technology                                    | Dimensionless |
| Actual average skill level                 | Actual skill level of the entire manpower   | Dimensionless |
| Training Requirement                       | Training needs to involve to improve average skill level of manpower                              | Dimensionless |
| Experienced sailors serving as Instructors | Numbers of experienced sailors serves as training instructors                                     | Person        |
| Crew size                                  | Numbers of crew in the system   | Person        |
| Complexity of technology                   | How complex of the state-of-the-art technology level in the system                                | Dimensionless |
| Automation Level                           | Level of automation after implemented State-of-the-art Technology. Range from level 1 to level 4. | Dimensionless |
| Pressure to adopt Training technology      | Increased training cost causes pressure changing on adopting new training technology              | Dimensionless |
| Manpower cost                              | Crew size increase manpower cost when other variables have no change                              | dollar        |

#### 5.1.4 Reference Modes

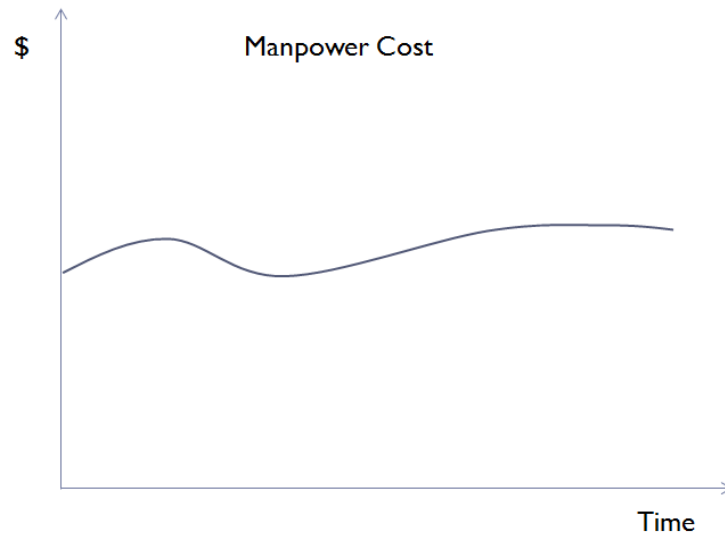


Figure 50: Reference Mode

The initial characteristics of the problem can be described by graphs for the modes of behavior along with changed time. The reference modes have abilities of describing these behaviors. By looking at the reference mode, stakeholders can get a clear picture format. Since manpower cost is the one of my major variables in the model, figure 50 depicts the model behavior over a certain time for the manpower cost estimation.

#### 5.1.5 Time Horizon

The time horizon is an important factor in the model development (Stermann 2000). A suitable time horizon enables delay structures and other dynamic behaviors in the model. It should not too long or

too short. In this model, a 10 years (120 months) time horizon is used since the technology is upgraded about every 18 months.

## 5.2 Formulation of Dynamic Behaviors

Formulation of dynamic behaviors is to develop a theory about the defined problem. It characterizes system behavior over the given time period.

Based on the literature review and model discussion with my committees, the following hypotheses were identified:

1. Increased implementation of numbers of advanced technologies decreases manpower cost.
2. Increased implementation of numbers of advanced technologies increases skill level required.

### 5.2.1 Mapping System Structure

#### 5.2.1.1 Model Boundary

A model boundary lists key variables and summarizes scope of the model including endogenous variables and exogenous variables in the model (Stermann, 2000). To illustrate, the following table shows a model boundary diagram for manpower cost drivers.

Table 11 Model Boundary

| Endogenous          | Description   | Exogenous                         | Description   |
|---------------------|---|-----------------------------------|---|
| Skill level         | Described by novice, intermediate, expert levels  | Automation Level                  | Different levels of automation in a ship system                                     |
| Crew Size           | The number of personnel accommodations on the ship (Enlisted) in terms of a Head-count. | Training requirement              | Requirement to improve manpower skills and to increase skilled numbers of personnel |
| Experienced sailors | Described by the number of E5 to E9   | Complexity of Technology to adopt | How complex of a new technology   |
| Workload            | Specified by Intermediate Maintenance workload  | Ship performance capability       | Increased by the new technology implemented   |

Automation level will be determined by the decision makers measuring from level 1 (very limited use of automation) to level 4 (very high use of automation). Optimizing the automation level is difficult for decision makers. On one hand, the automation would reduce workload and increase effectiveness for the sailors. On the other hand, higher levels of automation also increase the cost and risk of a system design.



### 5.2.2 Subsystem Diagram

Figure 51 depicts the detailed subsystem diagram. The purpose of this model is to explore manpower skill levels and crew size for a ship system. The ultimate goal is to estimate manpower cost associating with different technology implementation.

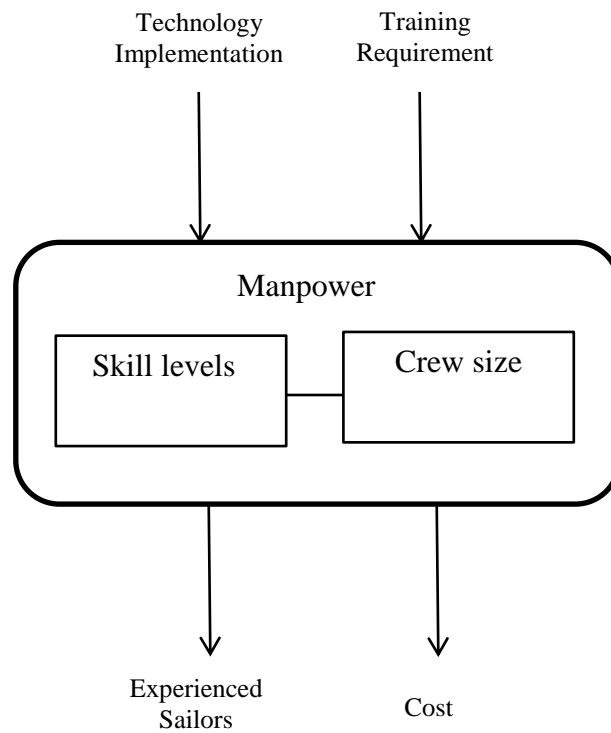


Figure 51: Subsystem Diagram

### 5.3 A Simulation Model Formulation

System Dynamics Modeling processes includes two important stages: (1) causal loop diagrams development and (2) the Stocks and Flows diagrams development. Causal loop diagrams identify key variables and capture relationship with other variables in the system. Stocks and Flows diagrams capture the mathematical functions of these variables. The following sections describe the causal loop and Stocks and Flows diagrams when implementing the state-of-the-art technology.

### 5.4 Causal Loop Diagrams

The key relationships in the model are shown in the following table and figures.

#### 5.4.1 Human System Integration (HSI) in the model

According to DoD instruction 5000.02 (US DoD, 2008), HSI is used to minimize TOC and optimize manpower at the same time. This method takes into consideration human capabilities and limitations during the phase of system designing. In this model, four parts are considered for HSI including manpower, personnel, training, and human factor engineering. As mentioned before, manpower considers the number and mix of personnel to operate and support system. Personnel focus on the cognitive and physical characteristics that need to operate, maintain, and sustain different systems. Training provides personnel with required skill, knowledge and ability

to meet requirements. Human factors engineering focuses on minimizing manpower but providing effective training to maintain system performance.

The purpose of HSI in military is to optimize manpower and workload without sacrificing system performance and system safety (Malone, 2003).

Table 12 Causal Loops Diagrams in details

| Loops | Name                                 | Section   | Describe  | Remark         | References   |
|-------|--------------------------------------|---|---|----------------|--|
| B1    | Technology affects System Capability | Capture sailors' skill level and numbers. Manpower cost | Need to Adopt State-of-the-Art<br>Technology $\rightarrow (+)$ State-of-the-art<br>Technology Implemented $\rightarrow (+)$ System<br>Performance Capability $\rightarrow (-)$ System<br>Performance Gap $\rightarrow (+)$ Need to Adopt<br>State-of-the-Art Technology | Balancing loop | Booher & Wiley (2003);<br>Bost & Galdorisi (2004);<br>; Carreno, Galdorisi & Lemon (2010);<br>Fleming (1997) |
| B2    | Training increases Skill levels      |   | Skill level Gap $\rightarrow (+)$ Training<br>Requirement $\rightarrow (+)$ Experienced<br>Sailors $\rightarrow (+)$ Actual average skill<br>level $\rightarrow (-)$ Skill level Gap  | Balancing loop | Adams & Rayhawk (1988); Bajracha rya, Ogunlana & Bach (2000);  |

| Loops | Name                                       | Section | Describe  | Remark         | References   |
|-------|--|---------|---|----------------|--|
| B3    | Automation level reduces crew size         |         | Manpower cost saving pressure→<br>(+)Need to Adopt State-of-the-Art Technology→(+)State-of-the-art Technology<br>Implemented→(+)Complexity of technology→(+)Automation level<br>→(+)Pressure to reduce crew size→(-)Crew Size→(+)Manpower Cost→(+)Manpower cost saving pressure | Balancing loop | Booher &Wiley (2003);<br><br>Douangaphaivong (2004);<br>Damle (2003);<br>Scofield (2006);<br><br>Personnel (2003);<br>Malone & Bost (2000);<br><br>MANPRINT Handbook (2005); |
| B4    | Less training time decreases training cost |         | Training cost→ →(+)Pressure to adopt Training technology→(-)Time to training all the trainees→(+)Training cost  | Balancing loop | Navy Manpower Analysis Center (2007);<br><br>Orlansky & String (1979);   |

| Loops | Name   | Section                           | Describe  | Remark           | References  |
|-------|--|-----------------------------------|---|------------------|---|
| B5    | Training Efficiency decreases cost                     |                                   | Training cost→(+)Pressure to adopt Training technology→(+)Numbers of State-of-the-art training technology Implemented→(+)Training efficiency→(-)training cost       | Balancing loop   | Simpson (1995); Orlansky & String (1979); Lockett-Reynolds & Duma (2009); |
| B6    | Ashore support decreases workload onboard              | Workload (Human factors Engineer) | Average Maintenance workload→(+)Pressure to transfer workload ashore→(+)Workload Transferred ashore→(-)Maintenance Workload onboard→(+)Average Maintenance workload | Balancing loop   | Scofield (2006); Runnerstrom (2003); Moore et al. (2002);                 |
| R1    | Productivity increases maintenance workload completion |                                   | Maintenance Completion rate→(-)Working overtime→(+)Fatigue→(-)Productivity→(+)Maintenance Completion rate   | Reinforcing loop | Runnerstrom (2003); Osga & Galdorisi (2003)                               |

*Remark: (+) means the two variables between links moving in the same direction, (-) means the two variables between links moving in the opposite direction.*

## 5.5 Model Description

The entire model serves the purpose of developing a model of describing the causes of problematic behavior and identifying major points. The following section describes seven loops in details.

### **B1: Technology affects System Capability**

Need to Adopt state-of-the-Art Technology → State-of-the-art Technology Implemented → System Performance Capability → System Performance Gap → Need to Adopt State-of-the-Art Technology

As **Manpower cost saving pressure** increases (Exogenous variable in this loop), so does the **Need to Adopt State-of-the-Art Technology**. The higher is the **Need to Adopt State-of-the-Art Technology**, the higher the number of **Technology needs to be implemented**. Once more **Technology is implemented** in the system, the **System Performance Capability** will increase. Higher **System Performance Capability** decreases the **System Performance Gap**. The less **System Performance Gap** is, the less is the **Need to Adopt State-of-the-Art Technology** in the system.

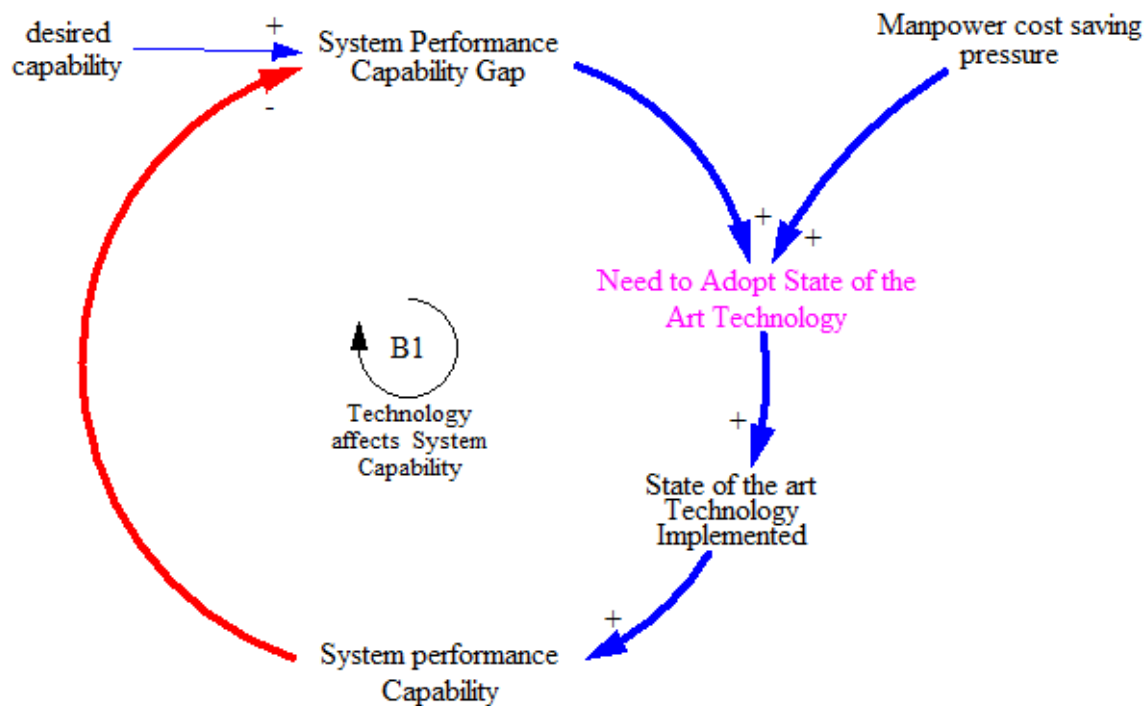


Figure 52: B1 Loop

## B2: Training increases skill levels

Skill level Gap → Training Requirement → Experienced Sailors → Actual average skill level required → Skill level Gap

As more State-of-the-art Technology is implemented in the system, it requires higher **Average skill level** for Sailors. The higher **Average skill level is required**, the higher the **Skill level Gap**, which increases **Training Requirement**. The higher **Training Requirement** will increase the number of **Experienced Sailors** after certain time of delay. Then as more **Experienced Sailors**

are added in the system, the **Actual average skill level** for the entire Ship system will increase.

The higher **Actual average skill level** is, the lower the **Skill level gap**.

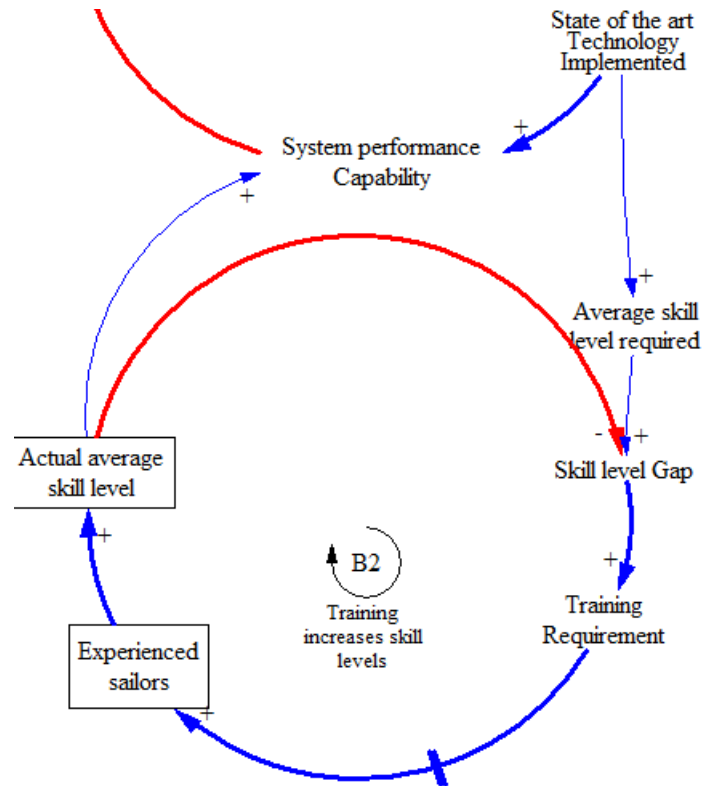


Figure 53: B2 loop

### B3: Automation level has potentiality to reduce crew size

Manpower cost saving pressure → Need to Adopt State-of-the-Art Technology → State-of-the-art Technology Implemented → Complexity of technology → Automation level → Pressure to reduce crew size → Crew Size → Manpower Cost → Manpower cost saving pressure



As **Manpower cost saving pressure** increases, so does the **Need to Adopt Technology**. The higher **Need to Adopt State-of-the-Art Technology** is, the higher numbers of **State-of-the-art Technology be Implemented**. Increased **Technology Implemented** leads to increased **Complexity of technology**. Then **automation level** of system will increase. Higher **automation levels** bring more **Pressure to reduce crew size**. **Crew Size** will be decreased by decision makers after certain times of delay. The decreased **Crew Size** will decrease **Manpower cost** if other variables have not caused any changes. Once **Manpower cost** decreases, **Manpower cost saving pressure** decreases too.

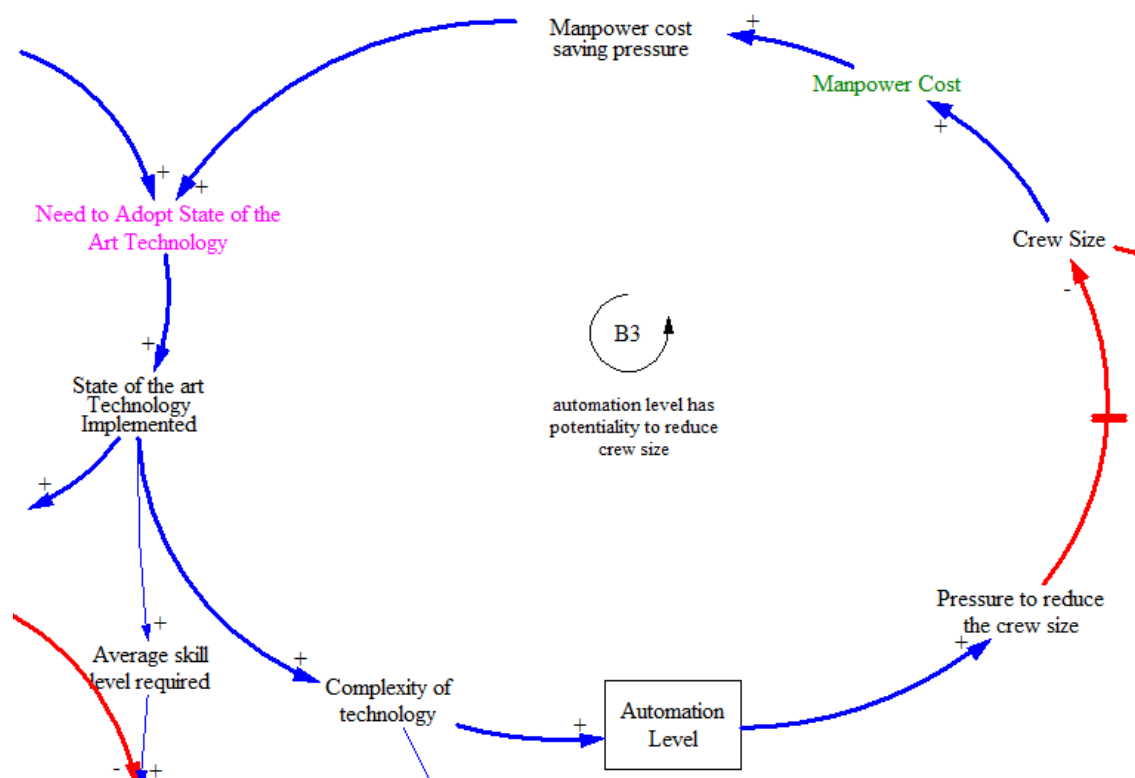


Figure 54: B3 loop

#### **B4: Experienced Sailors reduced training time**

Training cost → Pressure to reduce training time → Experienced Sailors serving as Instructors → Time Duration → Training cost

As **training cost** increases, the **Pressure to reduce training time** increases also. The higher Pressure to reduce training time is, the less Time to training all personnel. The less time for training, the less is the **Training cost**.

#### **B5: Training technologies decreases training cost**

Training cost → Pressure to adopt Training technology → Numbers of State-of-the-art training technology Implemented → Training Duration → training cost

As **training cost** increases, the **Pressure to adopt Training technology** increases also. The higher pressure to adopt Training technology, the more **training technology is implemented**. The more **training technology Implemented** decreases the **Training time**. Decreased training time decreases the **training cost**.

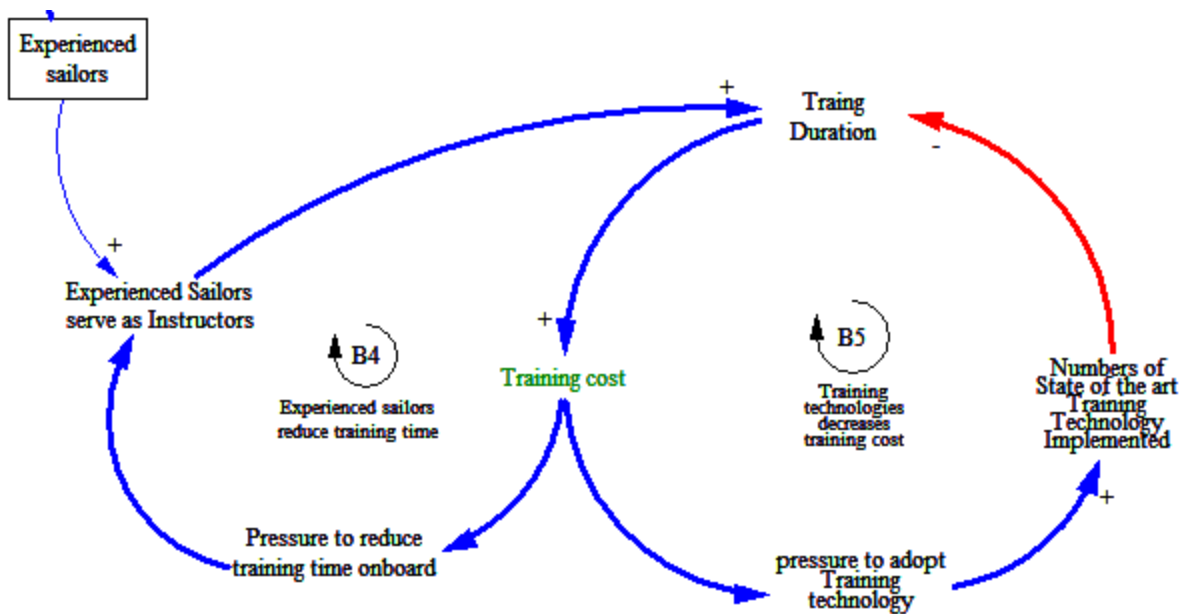


Figure 55: B4 and B5 loops

### R1: Productivity increases Maintenance Workload Completion

The higher **Maintenance Completion rate** decreases opportunities for **Working overtime**, leading to less **Fatigue**. Lower **Fatigue** brings higher **Productivity**. Higher **Productivity** will increase **Maintenance Completion rate**.

### B6: Ashore Support decreases Workload Onboard

Average Maintenance workload → Pressure to transfer workload ashore → Workload Transferred ashore → Maintenance Workload onboard → Average Maintenance workload

As **Average Maintenance Workload** increases, higher **Pressure to transfer workload ashore** in order to decrease onboard workload burdens. The more **Pressure to transfer workload**

**ashore** is, the more is the **Workload Transferred to ashore**. The more workload is transferred, the less is the overall **Maintenance Workload onboard**. Eventually the **Average Maintenance workload** will decrease under the same numbers of crew size.

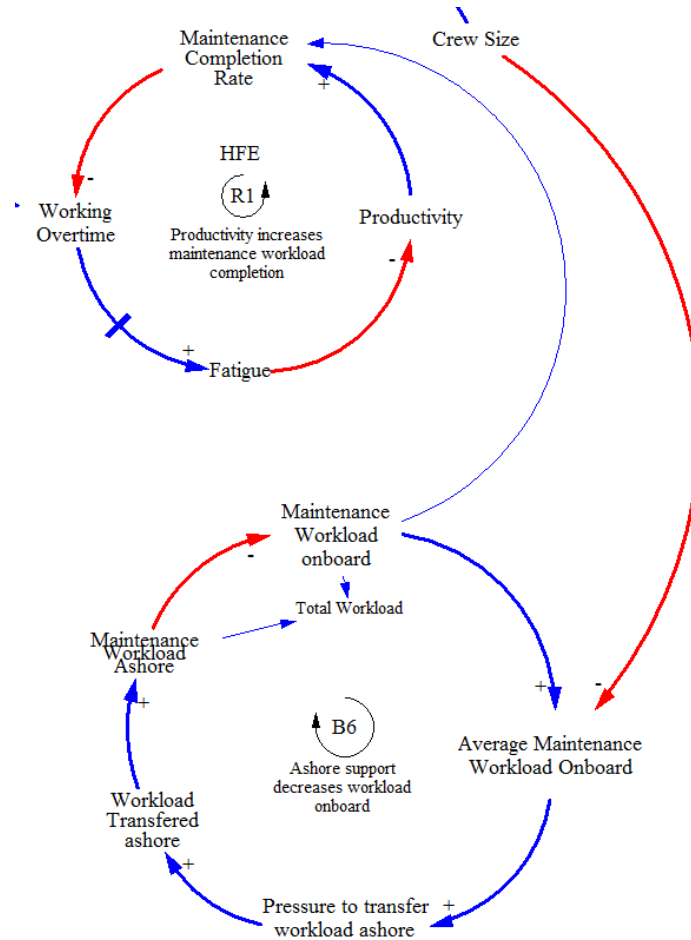


Figure 56: R1 and B6 loops

## 5.6 Stocks and Flows

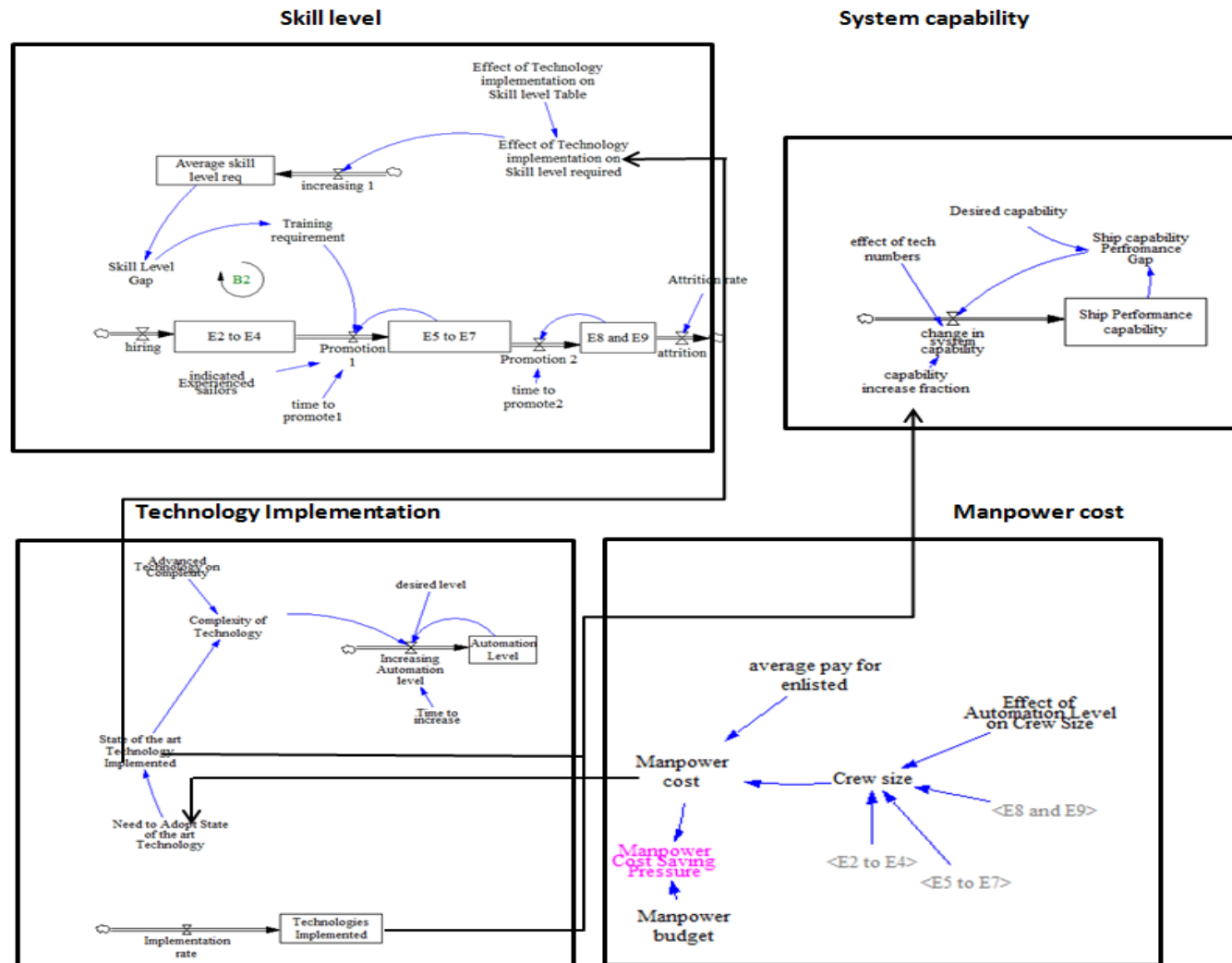


Figure 57: Base model sections

Figure 57 presents the Stocks and Flows diagram which includes four sections: system capability, technology implementation, skill levels and manpower cost. The key equations in the based model are discussed later.

#### 5.6.1 Model setting for Base Model

The base model parameters are shown in Table 13.

Table 13 Model Parameters value (source: Data modified from Navy Manpower Analysis Center and DDG-51)

| Variables                      | Values     |
|--------------------------------|------------|
| Initial Crew size              | 300 people |
| Experienced sailors (E5 to E7) | 100 people |
| Initial E2 to E4               | 190 people |
| Initial E8 and E9              | 10 people  |
| Time to Promotion 1            | 48 months  |
| Time to Promotion 2            | 120 months |

The base model specifies initial parameter values for different crew's skill levels. There are a total of 300 crew members at the beginning of the model which include 190 Enlisted level 2 to level 4, 100 Enlisted level 5 to level 7, and 10 Enlisted level 8 and level 9. The initial crew numbers are derived from crew members in the DDG-51 Arleigh Burke Class. Time to promotion from the novice to the intermediate is 48 months and Time to promotion from the

intermediate to the expert is 120 month. These data were modified from the Navy document data about years of experience for enlisted personnel.

The table 14 shows years of experience for Navy enlisted personnel. For example, normally it takes 4 years to 8 years to become an E-5 and take more than 15 years to become an E-9.

Table 14 Enlisted years of experience (data source: Williamson, 1999)

| Rank/Paygrades | Year of Experience |
|----------------|--------------------|
| E-1            | 1 year             |
| E-2            | 1-3 year           |
| E-3            | 2-4 year           |
| E-4            | 3-7 year           |
| E-5            | 4-8 year           |
| E-6            | 8-20 year          |
| E-7            | 12-20 year         |
| E-8            | >15 year           |
| E-9            | >15 year           |

Based on the information from this table above, the model initial settings for the promotion time are 4 years and 10 years for novice to intermediate and intermediate to expert respectively.

### 5.6.2 Technology Implementation

The base model shows a reference situation of the historical behavior from 2003 to 2012.

Technology insertion such as the Smart Ship program is able to achieve in reducing manning and maintain ship capability. Currently, the Navy continually implements a significant number of new technologies into ship systems. For example, DDG-1000 implements advanced technologies for reduced detectability, an integrated propulsion system, and automation technologies enabling a reduced-sized crew (O'Rourke, 2009). These technologies enable the ship system to operate in an advanced platform.

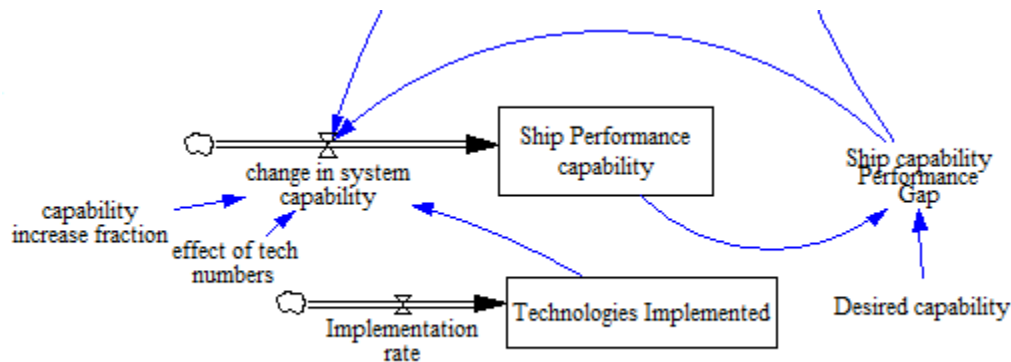


Figure 58: Stock and Flow of Technology Implementation

Figure 58 exhibits ship performance capability is impacted by numbers of technology implementation. The mathematic equation is listed in the following page.



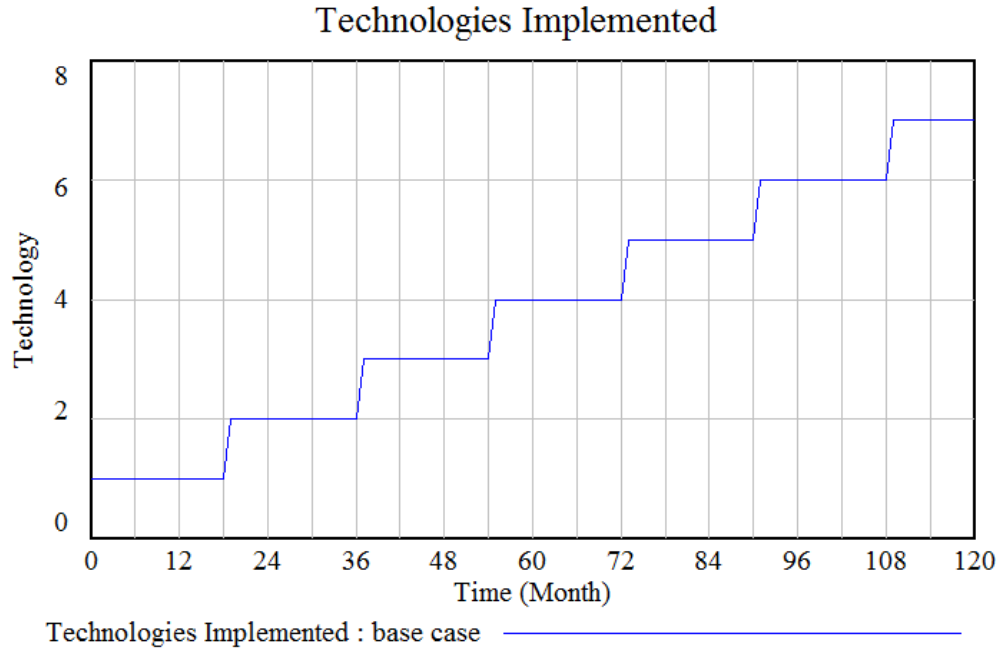


Figure 59: Numbers of technology implemented

From the opinion of the Subject Matter Expert (SME), the Navy implements new technologies every 18 month. Therefore, the base model used 18 month as the implementation rate of a new technology.

*Implementation Rate* =

$$PULSE(18,1) + PULSE(36,1) + PULSE(54,1) + PULSE(72,1) + PULSE(90,1) + PULSE(108,1) \quad (2)$$

$$Technologies\ Implemented = \int_0^t (Implementation\ Rate) * dt + Initial\ (TI) \quad (3)$$

TI: Technology Implementation

The figure 59 describes that every 18 months a new technology is implemented. Therefore, the number of technologies increases every 18 months. The number of technologies jumped to 7 after 10 years. Here the model made assumptions that there is only one new technology implemented in the system at the beginning of model running.

### 5.6.3 System Capacity

$$\begin{aligned}
 &\text{change in system capability} = \\
 &\text{capability increase fraction} * \text{Ship capability Performance Gap} * \\
 &\text{State of the art Technology Implemented} * \\
 &\text{effect of tech numbers (Technologies Implemented)}
 \end{aligned}
 \tag{4}$$

$$\text{Ship performance capability} = \int_0^t \text{change in system capability} * dt + \text{Initial SPC}
 \tag{5}$$

*SPC: Ship performance capability*

Ship performance capability changes from 1 to 10. The model assigned 1 is the lowest number and 10 is the highest number for ship capability.

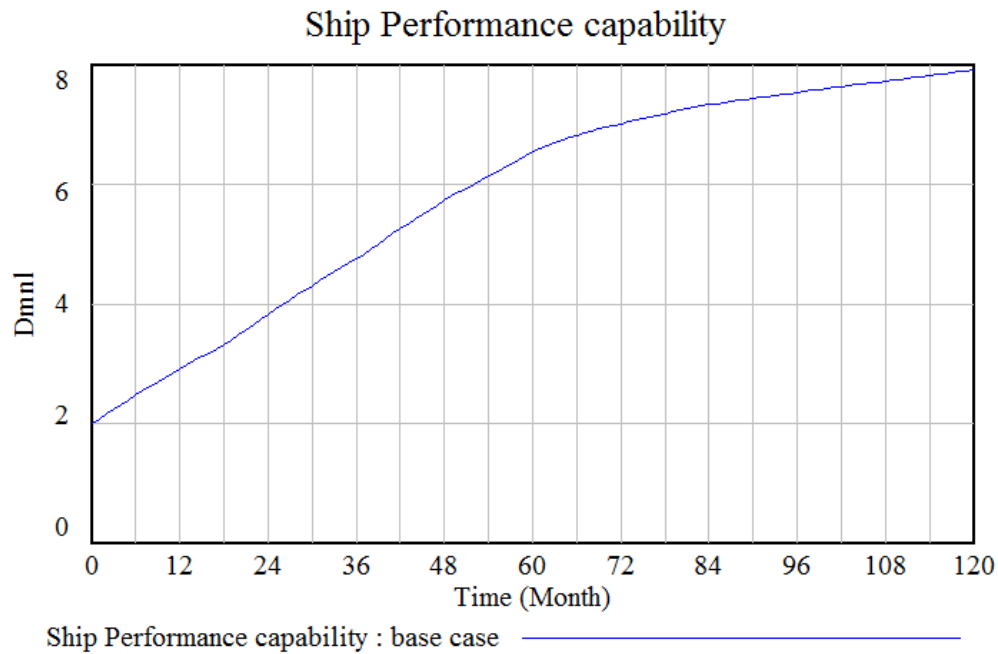


Figure 60: Ship Performance capability

Formula 4 and 5 showed that ship capability is determined by ship capability performance gap, new technology implemented, and the effect of the number of technologies implemented. Ship capability performance gap is one of factors determining ship performance capability. In addition, as more advanced technology is implemented into the system, ship performance capability increases. The model assumes that ship capability will improve when more and more technologies are implemented in the system.

## 5.6.4 Paygrade and Skill levels

### 5.6.4.1 Paygrade

The Navy manpower requirement system calculates different paygrade numbers by using staffing table. Figure 61 describes the paygrade matrix. For example, E-5 is the only one person assigned to the billet if only one personnel is needed. If more personnel are needed, E-3 to E-6 will be assigned to the billet. E-1 is given to a new high school graduate recruited. The subsequent trainings will be provided either by the Navy or by a civilian institution to enable sailors move up to the higher levels.

| Number<br>in rating | Percentage in paygrade |    |    |     |    |    |            | All |
|---------------------|------------------------|----|----|-----|----|----|------------|-----|
|                     | Non-<br>desig.         | E3 | E4 | E5  | E6 | E7 | E8 &<br>E9 |     |
| 1                   | 0                      | 0  | 0  | 100 | 0  | 0  | 0          | 100 |
| 5                   | 0                      | 20 | 40 | 20  | 20 | 0  | 0          | 100 |
| 10                  | 20                     | 10 | 30 | 20  | 10 | 10 | 0          | 100 |
| 20                  | 25                     | 10 | 30 | 15  | 15 | 0  | 5          | 100 |
| 30                  | 27                     | 10 | 27 | 13  | 13 | 7  | 3          | 100 |
| 50                  | 22                     | 8  | 32 | 16  | 12 | 6  | 4          | 100 |
| 70                  | 24                     | 7  | 31 | 16  | 11 | 7  | 2          | 100 |
| 90                  | 26                     | 8  | 31 | 16  | 11 | 7  | 2          | 100 |
| 110                 | 25                     | 7  | 32 | 15  | 11 | 6  | 3          | 100 |
| 130                 | 26                     | 7  | 30 | 16  | 12 | 7  | 3          | 100 |
| 150                 | 25                     | 7  | 31 | 16  | 11 | 7  | 2          | 100 |

Figure 61: Paygrade Matrix (source: Data adapted from Navy Manpower Analysis Center, 2007)

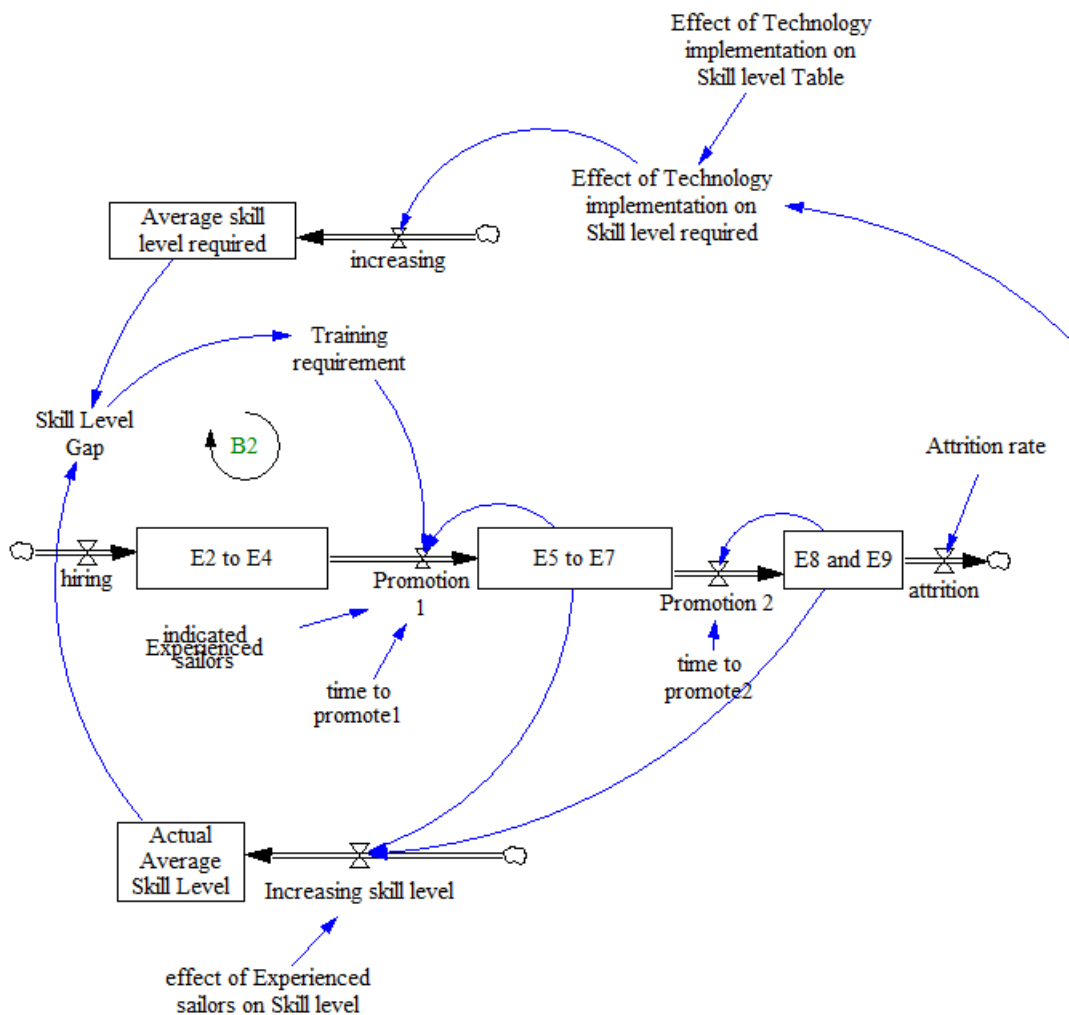


Figure 62: Stock and flow diagram of paygrade levels

Figure 62 showed three major categories of enlisted paygrade levels in the model.

#### 5.6.4.2 Skill levels

Paygrades E1 to E9 reflect levels of training, experience, knowledge, skill, and responsibility.

According to the Navy Budget documents, Pay and allowance of Enlisted include different pay

for example, the basic pay and special pays. Since this research considers enlisted sailors from the E-2 to E-9, the following two tables lists numbers and key requirements for different levels. In addition, these levels are divided into three major groups, which are the novices, intermediate and expert levels. The average pay was calculated based on these two numbers. Table 15 lists the skill levels and key requirement for E-2 to E-9.

Table 15 Manpower skill levels description (source: Manual of Navy Enlisted Manpower and Personnel Standard, 2011)

| Manpower skill levels |         | Key requirement  | Examples   |
|-----------------------|---------|--|--|
| Novices skillset      | E2---E4 | Basic knowledge of ships and officer rates                                     | Maintain log and files   |
| Intermediate Skillset | E5---E7 | Performance evaluation, assign works to subordinates, and providing trainings. | Aviation technician  |
| Expert Skillset       | E8---E9 | Technical expert, authority and management skills                              | Supervising and training enlisted personnel oriented to system |

Table 16 lists the reference for different percentage and number of skillsets of enlisted sailors based on information from Navy Manpower Analysis Center.

Table 16 Numbers of Skillsets (source: Data adapted from Navy Manpower Analysis Center, 2007)

|                        | E-1 | E-2      | E-3 | E-4 | E-5      | E-6 | E-7 | E-8&E-9 | Total |
|------------------------|-----|----------|-----|-----|----------|-----|-----|---------|-------|
| Percentage             | 1%  | 25%      | 7%  | 31% | 16%      | 11% | 7%  | 2%      | 100%  |
| 300 sailors            | 3   | 75       | 21  | 93  | 48       | 33  | 21  | 6       | 300   |
| Number by skill levels | 3   | 189(63%) |     |     | 102(34%) |     |     | 6(2%)   |       |

Based on the table above, calculations can be completed for different paygrade levels. The E2 to E4 is 189, E5 to E7 is 102 and E8 to E9 is 6. The calculation is based on 300 onboard for the DDG-51 class. Therefore, the model settings of initial numbers are round up from the numbers of the table above.

Furthermore, crew cost data are needed to acquire in order to do model testing. The public data from DoN Budget estimate do not provide that type of data. The following table shows details of paygrade for 300 enlisted sailors from 2003 to 2012.

Table 17 Paygrade for 300 Enlisted Personnel (source: Data adapted from DoN Budget estimate 2003-2012)

|      | (1)                     | (2)                | (3)                                  | (4)                    | (5)                            |
|------|-------------------------|--------------------|--------------------------------------|------------------------|--------------------------------|
|      | DoN data (in thousands) | Enlisted personnel | Average pay per year per sailor (\$) | According to 300 crews | 300 crew cost per month(\$/12) |
| 2003 | 16,035,569              | 320457             | 50039.69019                          | 15,011,907             | 1,250,992                      |
| 2004 | 15,937,469              | 312249             | 51040.89685                          | 15,312,269             | 1,276,022                      |
| 2005 | 16,777,226              | 302820             | 55403.29569                          | 16,620,989             | 1,385,082                      |
| 2006 | 14,965,766              | 289450             | 51704.14925                          | 15,511,245             | 1,292,604                      |
| 2007 | 15,019,960              | 278193             | 53991.15003                          | 16,197,345             | 1,349,779                      |
| 2008 | 15,418,559              | 275963             | 55871.83427                          | 16,761,550             | 1,396,796                      |
| 2009 | 16,807,552              | 273448             | 61465.25848                          | 18,439,578             | 1,536,631                      |
| 2010 | 17,165,910              | 270715             | 63409.52662                          | 19,022,858             | 1,585,238                      |
| 2011 | 17,559,370              | 265187             | 66215.04825                          | 19,864,514             | 1,655,376                      |
| 2012 | 17,696,433              | 259876             | 68095.68025                          | 20,428,704             | 1,702,392                      |

In this table, column (1), (2), and (3) are the data from the DoN website. Column (4) was calculated based on the 300 crew members on the DDG-51 onboard. Column (5) is a monthly data calculated from the column (4).

#### 5.6.5 Crew Size

The goal of manpower requirements is to determine the minimal crew size but meanwhile to maintain a desired system capability (Navy Manpower Analysis Center, 2001).

In this model, the equation of crew size is as follows:



$$\text{Crew size} = \text{Min (Effect of Automation Level on Crew Size (Automation Level), (E5 to E7 + E2 to E4 + E8 and E9))} \quad (6)$$

The equation expressed the effort of minimizing the number of crew size onboard to decrease manpower cost. As we know, the higher automation levels require less crew size. The equation attempted to express the effect of different levels of automation for reducing the number of crew sizes. Automation levels improve when implementing new technology. This equation could provide decision makers the information for frequency to implement new technologies.

#### 5.6.6 Manpower cost

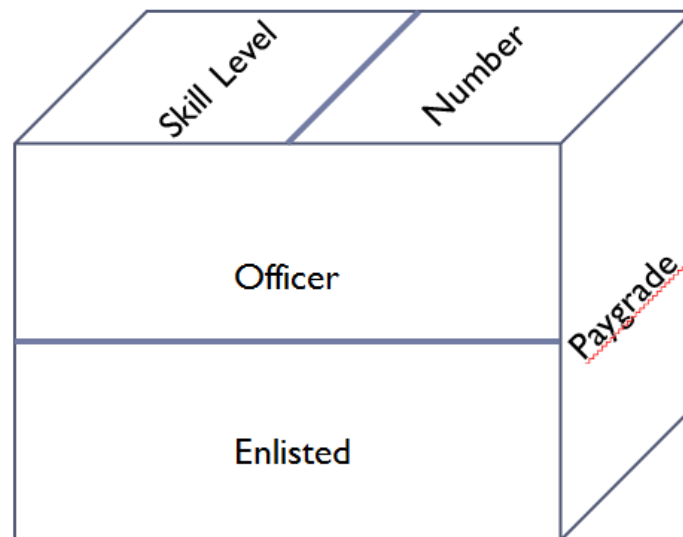


Figure 63: Manpower cost architecture (scope)

Figure 63 displays manpower model's scope specified by skill level, number, and paygrade.

Manpower cost architecture describes components of manpower cost. Manpower cost includes cost for officers and enlisted personnel. Skill level and number of personnel are embedded into

the cost of officers and enlisted personnel. Officers and enlisted personnel also have different paygrade levels.

Although manpower cost components include compensations for both Officers and Enlisted, officer compensation is only approximately 17% of the manpower cost of a ship system. Enlisted manpower cost accounts for 83% of the cost. This research used enlisted skill levels to estimate manpower cost. Future study needs to involve Officers' cost in the model.

Based on the information from the Navy, three major categories are identified for formulations of this model. There are three skill levels for different skillsets including novices, intermediates, and experts. Novices have the basic knowledge of the ship and report to their supervisors. Intermediates provide training, evaluate their subordinates and assign works to them. Experts have more responsibilities for supervising and training enlisted personnel.

Ting (1993) built a mathematical relationship for the Navy manpower operation and support system based on the data of 652 ships. He grouped 652 ships into 11 groups and calculated the average annual pay of both officers and enlistees. He assigned manpower as the dependent variable, the number of officers (OFFNAVY) and enlistees (ENLNAVY) were the independent variables for each ship.

Based on Ting's model, manpower cost can be expressed by the following equations:

$$f(\text{Manpower cost}) = \alpha_0 + \alpha_1 \text{Officer} + \alpha_2 \text{Enlisted} + \epsilon \quad (7)$$

Compensation for different paygrade includes basic pay, allowance, entitlement, bonus, and Retirement items. The following equations express the relationship of paygrade for officers and enlisted personnel.

$$\text{Officer } \alpha_1 = \text{BasicPay} + \text{Allowance} + \text{Bonus} + \text{Entitlement} + \text{FICA} + \text{Retirement} + \text{MERHC} + \epsilon \quad (8)$$

$$\text{Enlisted } \alpha_2 = \text{BasicPay} + \text{Allowance} + \text{Bonus} + \text{Entitlement} + \text{FICA} + \text{Retirement} + \text{MERHC} + \epsilon \quad (9)$$

In this research, only the enlisted sailors were considered in the model. Therefore, the equation for the manpower is revised as follows:

$$f(\text{Manpower cost}) = \alpha_0 + \alpha_1 \text{Enlisted} + \epsilon \quad (10)$$

$$\text{Enlisted } \alpha_1 = \text{BasicPay} + \text{Allowance} + \text{Bonus} + \text{Entitlement} + \text{FICA} + \text{Retirement} + \text{MERHC} + \epsilon \quad (11)$$

The data for the enlisted personnel can be acquired from the DoN Budget materials website. The website includes data for personnel, operation& maintenance, construction, procurement, R&D and overseas operations.

From the data acquired from the website, the average number of personnel Enlisted per ship had been steadily decreasing. Figure 64 shows the behavior of enlisted personnel. Advanced

technologies will require not more sailors but more skilled sailors. In recent years, the Navy hires higher grade levels of sailors to maintain high productivity.

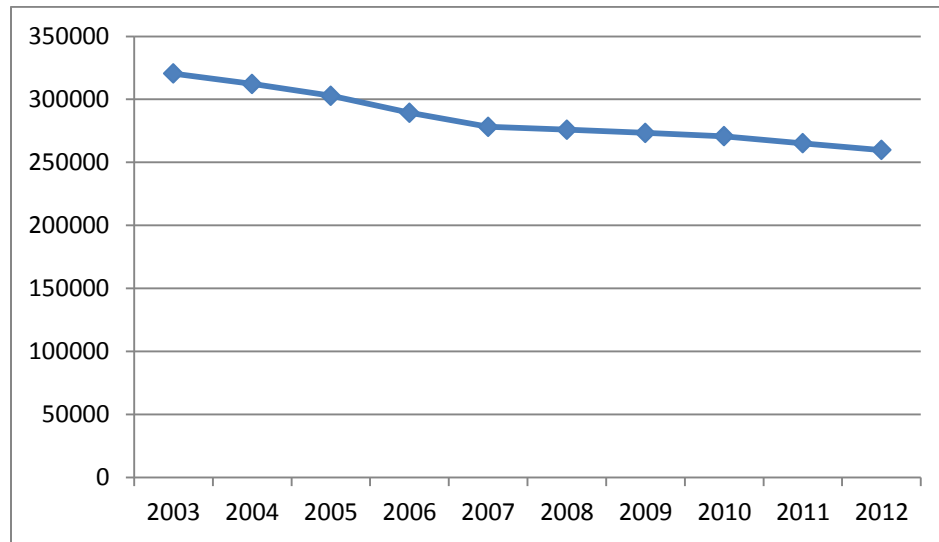


Figure 64: DoN Data of Enlisted personnel from 2003 to 2013 (source: Data adapted from DoN Budget Estimates)

Figure 65 depicts the diagram for manpower cost and crew size. As automation level increases, it decreases crew size in the system. The varying of manpower cost depends on crew size and average pay for enlisted personnel.

$$\text{Manpower cost} = \text{Crew size} * \text{average pay for enlisted} \quad (12)$$

Equation 12 also specified the relationship for manpower cost. It changes along with changing crew size and changing the average pay for enlisted personnel.

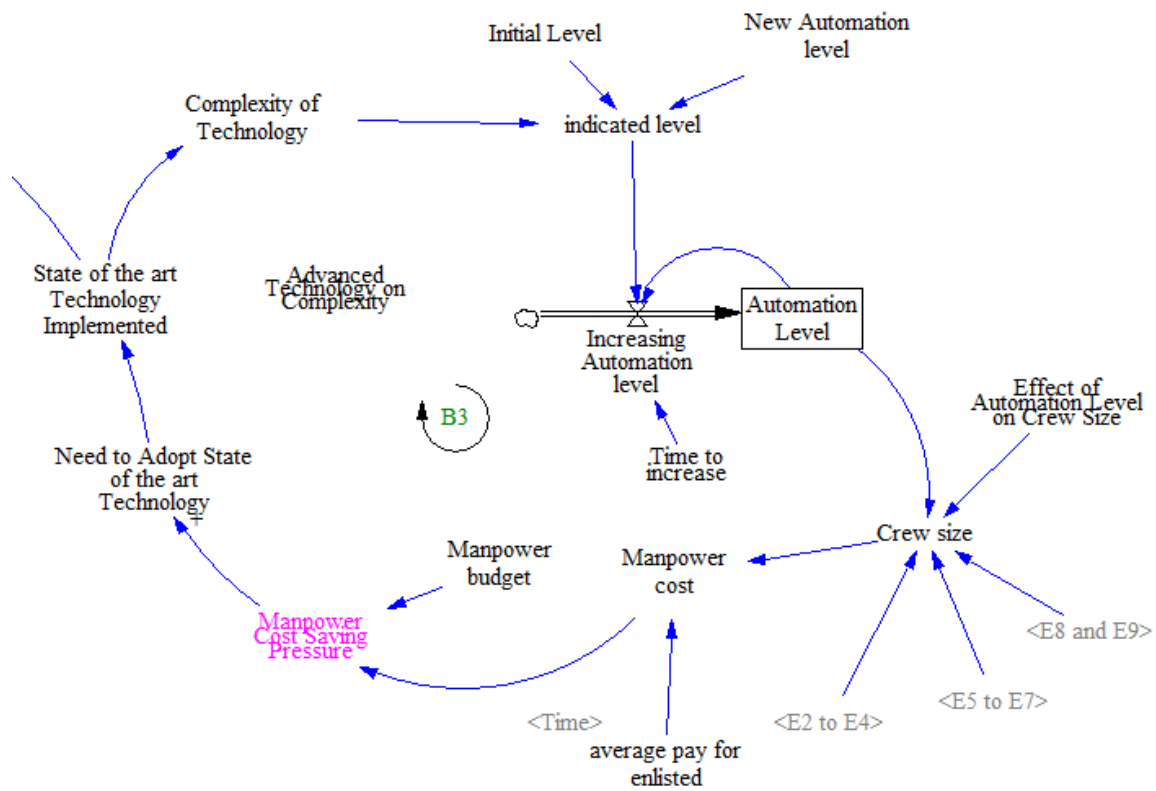


Figure 65: Stock and flow diagram of the Manpower cost and Crew size

### 5.6.7 Training cost

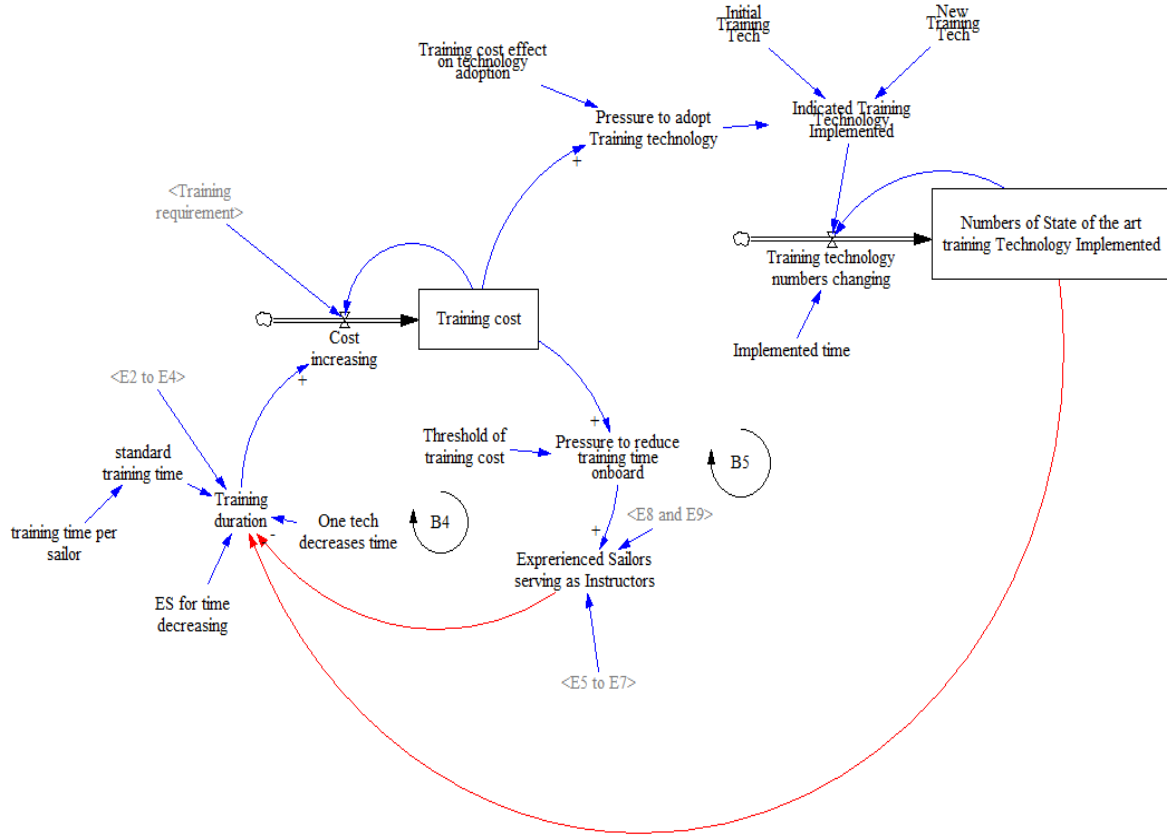


Figure 66: Stock and Flow diagram for Training Cost

#### 5.6.7.1 Factors affecting training cost

In the training cost model, training requirements and training duration are two factors that have impacts on training cost. Training requirements increase in conjunction with increased skill level gaps. Increased training duration also increases training cost. However, more training technologies such as simulation can reduce training time, eventually decrease training cost. In addition, more experienced sailors serving as instructors also decreases training duration. The

Navy provides extensive cross-training to create a more skilled labor force. Computer Based Training (CBT) is in some ways more cost-effective, depending on class size and length of use.

Navy training systems reduce training time through CBT and offering distributed learning opportunities that could be executed at the workplace. In this model, training technology is one way of reducing training duration. Another way is to involve more experienced sailors serving as instructors. Training technology such as simulation is a productive method to increase training efficiency. Different training simulators have been applied in the ship system for crew members' training purpose. By using the Synthetic Virtual Environment (SNE) for maintenance training, the Navy will improve the training efficiency of training onboard for sailors.

Training cost equation:

$$\text{Training Cost} = \int_0^t \text{Cost Increasing} * dt + \text{Initial Training cost} \quad (13)$$

On-the-job training (OJT) is the type of training considered in this model. Although more than a thousand formal courses are taught in the Navy schools, a sufficient amount of on-the-job training (OJT) is conducted in ship. On-the-job training (OJT) involves personnel with more experience teaching those with less experience how to perform tasks, such as watch standing, plotting the ship's course, using a radar system.

#### 5.6.7.2 Ship Operational Support and Training data

Training elements of DoN Budget reports from FYs 2003 to 2012 were analyzed to determine the amount of money spent on training each year through these years. Ship Operational Support and Training data were used in this model development process.

According to the Navy, Ship Operational Support and Training provides factors necessary to ensure that ships and their crews operate at high levels of readiness. Surface support is one example of Ship Operational Support and Training.

Table 18 Operation and Support training data (source: Data adapted from DoN Budget Estimates)

| Data                          | 2003          | 2004          | 2005          | 2006          | 2007          | 2008          | 2009          | 2010          | 2011          | 2012          |
|-------------------------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| DoN data<br>(in<br>thousands) | 634,02<br>8   | 641,47<br>0   | 616,5<br>49   | 620,76<br>2   | 631,93<br>6   | 709,48<br>0   | 683,20<br>3   | 709,38<br>7   | 810,20<br>5   | 736,51<br>2   |
| Number of<br>ships            | 297           | 292           | 282           | 281           | 278           | 282           | 285           | 288           | 285           | 283           |
| Annually<br>Average(\$)       | 2,134,7<br>74 | 2,196,<br>815 | 2,186,<br>344 | 2,209,1<br>17 | 2,273,1<br>51 | 2,515,<br>887 | 2,397,<br>204 | 2,463,1<br>49 | 2,842,<br>825 | 2,602,5<br>16 |
| Monthly<br>Average(\$)        | 177,89<br>8   | 183,06<br>8   | 182,1<br>95   | 184,09<br>3   | 189,42<br>9   | 209,65<br>7   | 199,76<br>7   | 205,26<br>2   | 236,90<br>2   | 216,87<br>6   |

Table 18 showed data from DoN Budget Estimates for Operations and Maintenance (O&M) reports from FYs 2003 to 2012. The data from Ship Operation and support training was used in the model for estimating training cost and testing the model. Figure 67 showed the monthly average numbers of the training cost for each ship. These data were calculated from annually DoN Data.



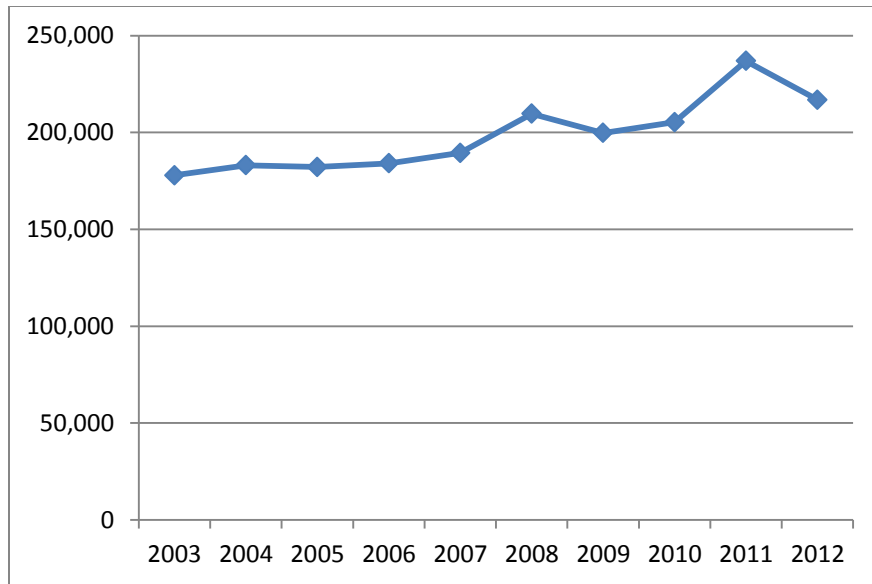


Figure 67: DoN Data of monthly training cost (source: DoN Budget Estimates, 2003-2012)

All budget reports included 3 years of budget data. For instance, the FY2005 report included budget data for FYs 2003, 2004, and 2005. The numbers contained in the report represent the Total Obligation Authority (TOA) for the given FY in the last year it was reported.

#### 5.6.8 Maintenance workload

It is important to clarify workload categories in order to understand manpower requirements for the Navy. Manpower requirements are determined by different workloads and should be calculated to accomplish mission readiness at the minimum levels.

In this model, maintenance workload is considered since it is one factors of defining manpower requirements. Currently it is not possible to obtain maintenance workload data from a public

domain for a specific type of a ship system. However, it is necessary to check the logic and do mathematical analysis for maintenance workload for the future study.

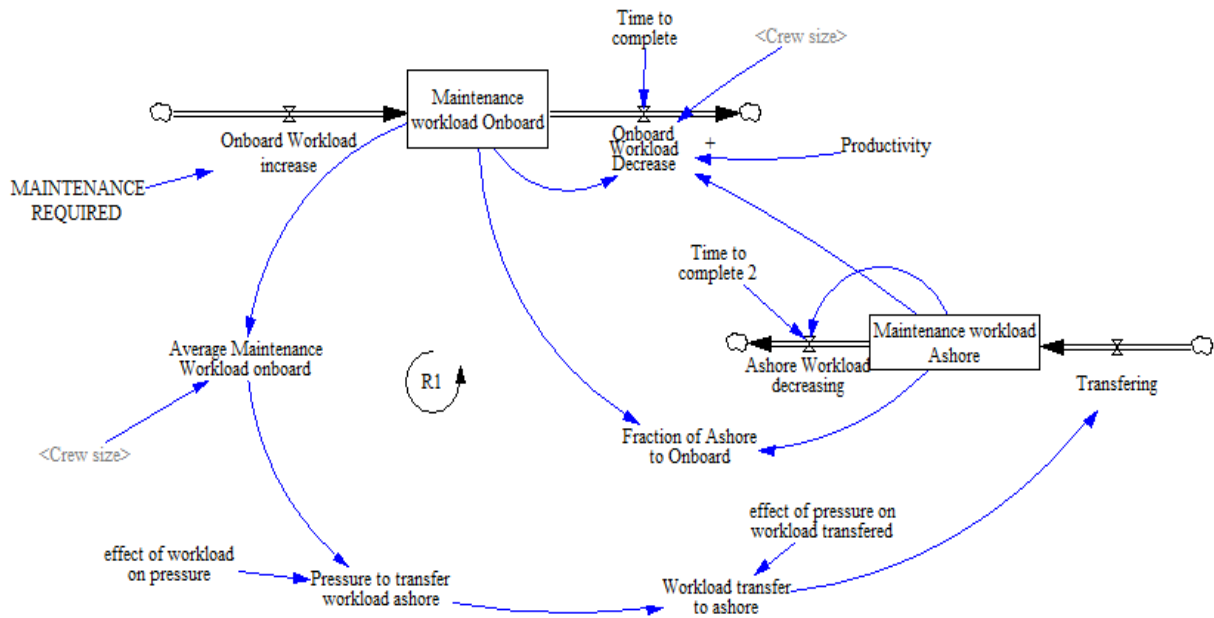


Figure 68: Stock and Flow diagram for Maintenance Workload

Figure 68 presents the logic for maintenance workload transferring. One way to reduce maintenance workload onboard is to transfer onboard maintenance workload to ashore. Workload transferring sought to reduce the workload onboard. The ultimate goal is to reduce the average maintenance workload onboard and improve habitability for crew members. Transferring workload to ashore enables crew members' habitability and reduces fatigue level. The following equations are used to assess the dynamic behavior of maintenance workload onboard and ashore in the model.

*Maintenance workload Onboard =*

$$\int_0^t (\text{Onboard Workload increase} - \text{Onboard Workload Decrease}) * dt + \text{initial onboard workload} \quad (14)$$

$$\text{Maintenance workload Ashore} = \int_0^t (\text{Transferring} - \text{Ashore Workload decreasing}) * dt + \text{initial ashore workload} \quad (15)$$

The DoN has the instruction for ship maintenance. The actions of ship maintenance are critical since they are designed to ensure crew and ship safety while achieving desired operational readiness levels at the lowest TOC.

There are three different maintenance levels which include organizational maintenance (O-level), Intermediate maintenance and Depot maintenance (D-level).

In this research, I-level maintenance was considered in the model. According to the DoN definition for the Intermediate-level (I-Level) maintenance, I-level maintenance requires higher requirements than those of the organizational level but do not necessarily require depot-level skills, facilities, or capacities. I-level maintenance work includes a lot of workload such as preventive maintenance, inspections, and repair services. I-level maintenance is done by designated maintenance activities in support of ship units.

I-level was chosen for this because it includes PM and CM and it is the major maintenance which occurs onboard. Preventive maintenance (PM) and corrective maintenance (CM) projects can be distinguished by degrees of urgency and orders of work content of the projects. CM is

assigned to crew members once a system fails (Keizers et al., 2003). In addition, CM has absolute priority over PM, which can seriously interrupt any process of the PM projects.

## **CHAPTER SIX: RESULTS, TESTING OF MODELS**

The model is validated by two types of data. One is manpower cost and another one is Operation and Support training cost. The data was acquired from the public domains of the Department of the Navy (DoN).

The simulation confirmed the prior theory and initial hypothesis, which increased implementing of the numbers of the state-of-the-art technologies decreases manpower cost.

### **6.1     Simulation Run and Results**

#### **6.1.1 Manpower cost**

The input of the simulation is the technology implementation. The output variables include crew size, manpower cost, and training cost. These match with the objectives of this research. Figure 69 exhibits the behavior of manpower cost for a ship system in the next ten year. The model was validated by the average annual data for a ship system. In addition, manpower cost showed here is the average monthly data after calculation.

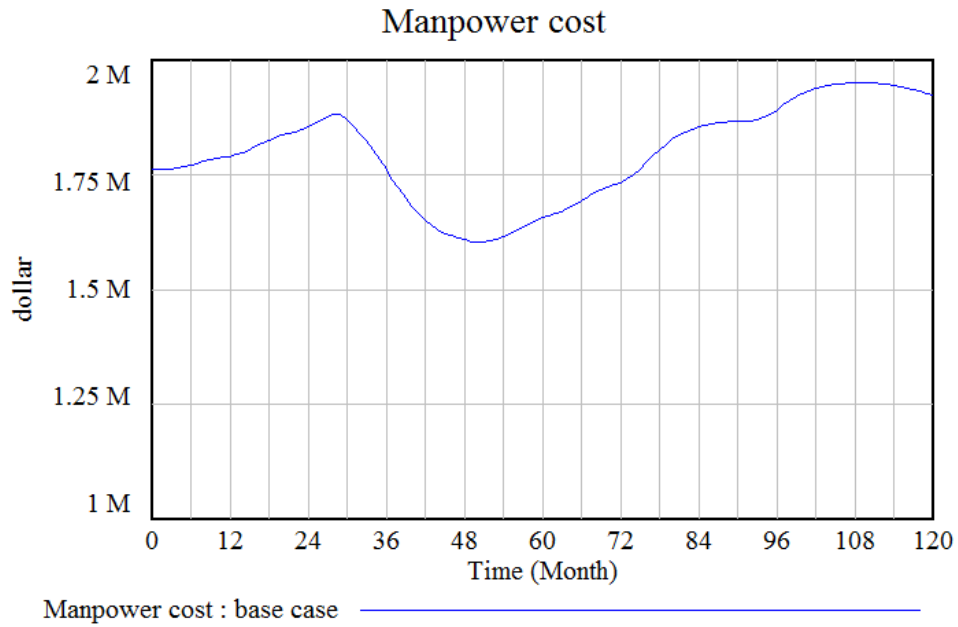


Figure 69: Model running for the next ten year from 2013

Figure 69 and table 19 describes the forecasting data for the next ten years. Manpower cost will increase in the first three years and then drop in the next few years. Eventually it will steadily increase for the rest of years.

Table 19 Monthly average manpower cost forecasting (model result)

| 2013    | 2014    | 2015    | 2016    | 2017    | 2018    | 2019    | 2020    | 2021    | 2022    |
|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| 1773723 | 1824635 | 1863162 | 1735348 | 1676874 | 1711758 | 1818558 | 1885529 | 1952387 | 1971439 |

Table 20 describes comparison between the DoN Data and model running result.

Table 20 Manpower cost between DoN and modeling running result

|                  | 2003      | 2004      | 2005      | 2006      | 2007      | 2008      | 2009      | 2010      | 2011      | 2012      |
|------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| DoN data         | 1,250,992 | 1,276,022 | 1,385,082 | 1,292,604 | 1,349,779 | 1,396,796 | 1,536,631 | 1,585,238 | 1,655,376 | 1,702,392 |
| Modeling Running | 1,234,597 | 1,298,914 | 1,340,478 | 1,253,419 | 1,284,227 | 1,383,246 | 1,517,347 | 1,603,318 | 1,691,382 | 1,723,127 |

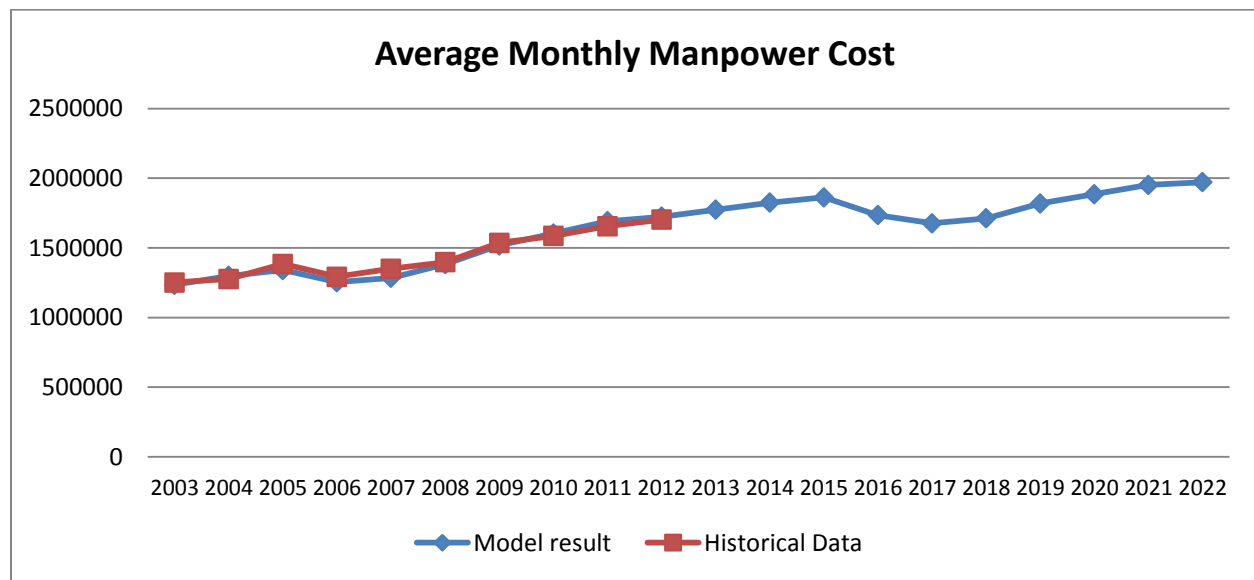


Figure 70: Manpower cost calibration and forecasting

Figure 70 exhibited the model validation by using historical data and model forecasting of the next ten years. Manpower cost increases steadily in the next ten years. It increases 14 percent in comparison to the data of 2012. The historical timeframe was selected for model testing from 2003 to 2012. The figure showed the average monthly manpower cost.

### 6.1.2 Training Cost

Figure 71 describes the model validation by using historical data and model forecasting for the training cost. In the next ten years, training cost increases steadily. It will increase 6.5 percent compared to the data of 2012.

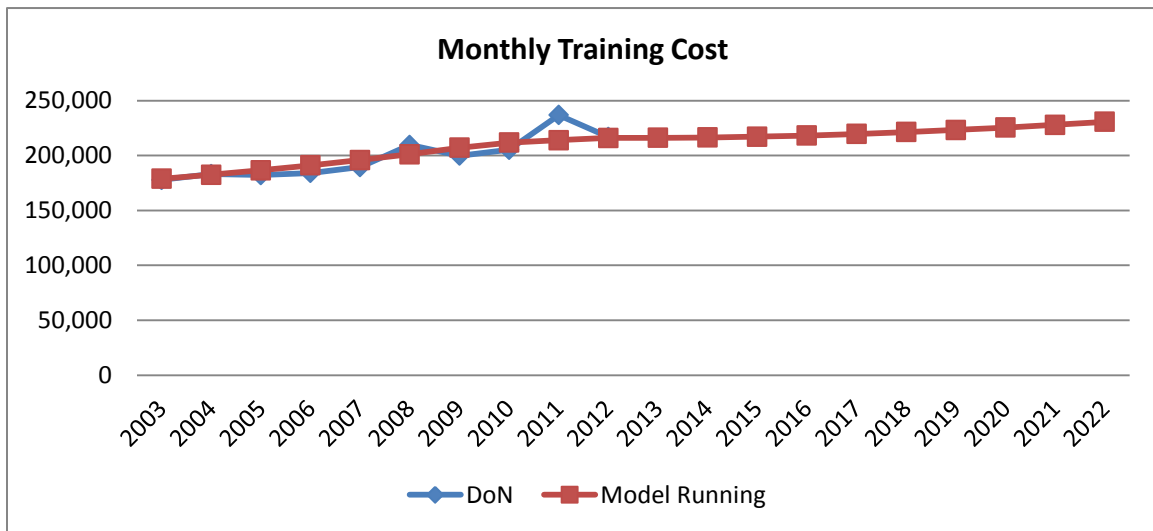


Figure 71: Monthly training cost calibration and forecasting

Table 21 lists the model result for the next ten years starting from 2013 to 2022. Onboard training cost will steadily increase 6.5 percent in 2022 compared with the number in 2013.

Table 21 Monthly training cost forecasting

| 2013      | 2014      | 2015      | 2016      | 2017      | 2018      | 2019      | 2020      | 2021      | 2022      |
|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| \$216,127 | \$216,510 | \$217,193 | \$218,249 | \$219,644 | \$221,345 | \$223,320 | \$225,543 | \$228,016 | \$230,758 |



### 6.1.3 Maintenance Workload

The maintenance workload sub-model is used to check the logic and do mathematic analysis for maintenance workload for the future study. Figure 72 showed the result of maintenance workload onboard. In the first seven years, onboard maintenance workload increases evenly, and then it increases steeply for the following three years.

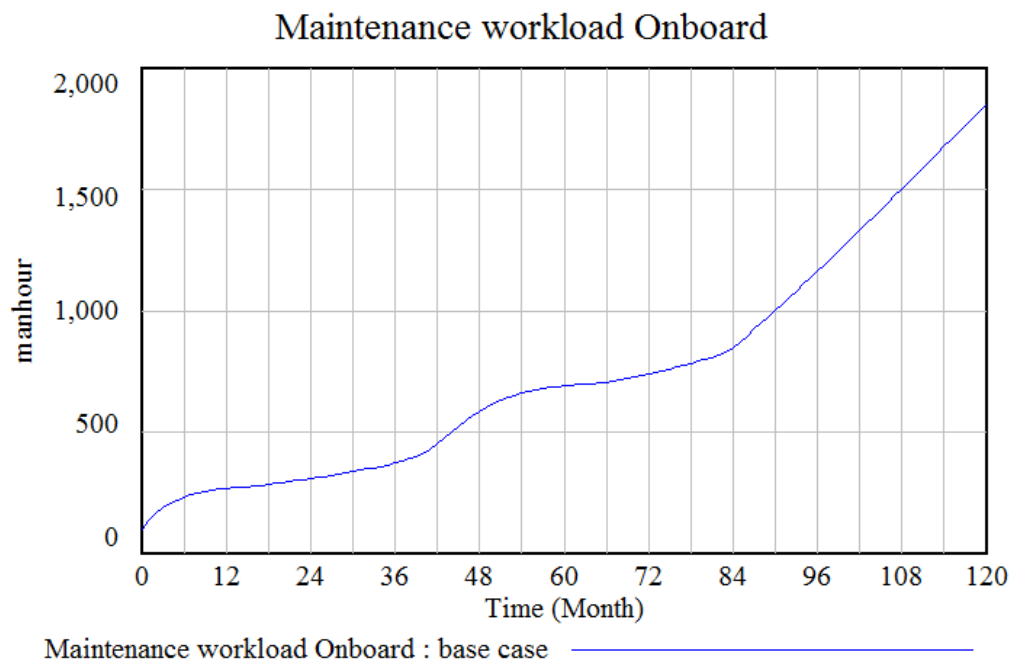


Figure 72: Maintenance workload onboard

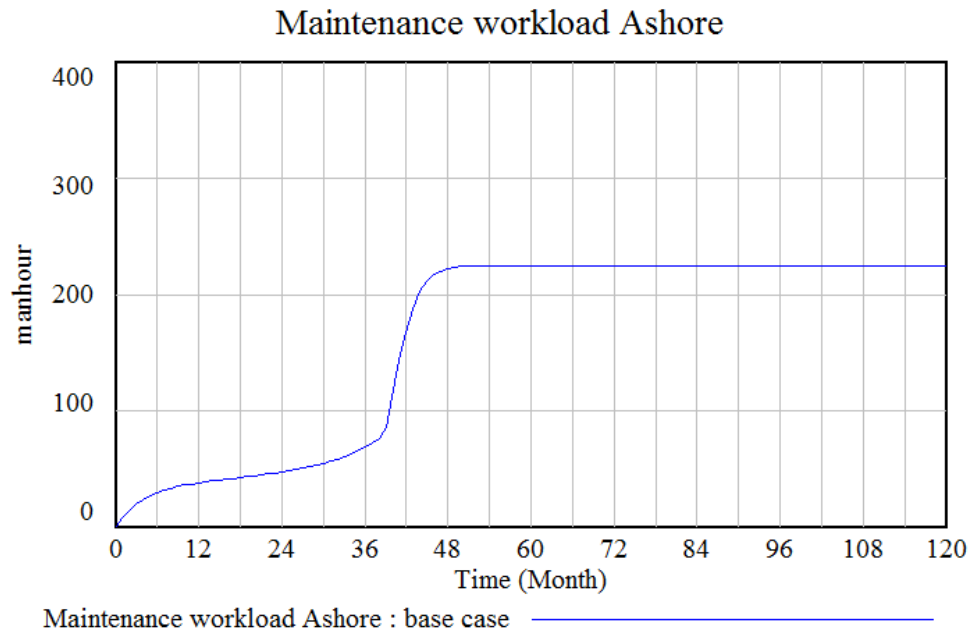


Figure 73: Maintenance workload ashore

Figure 73 described the result of workload transferred to ashore. In the first four years, workload transferred more and then reached to the limit in the rest of model running years. The model assumed that 225 man-hours is the maximum workload which maintenance can handle in the shore.

## 6.2 Sensitivity analysis

This analysis is used to robust model behaviors. By changing the input value of the model, a sensitivity analysis is carried out. The following figure exhibits three scenarios for different technology implementation rates, which are 0, every 18 months and every 26 months.

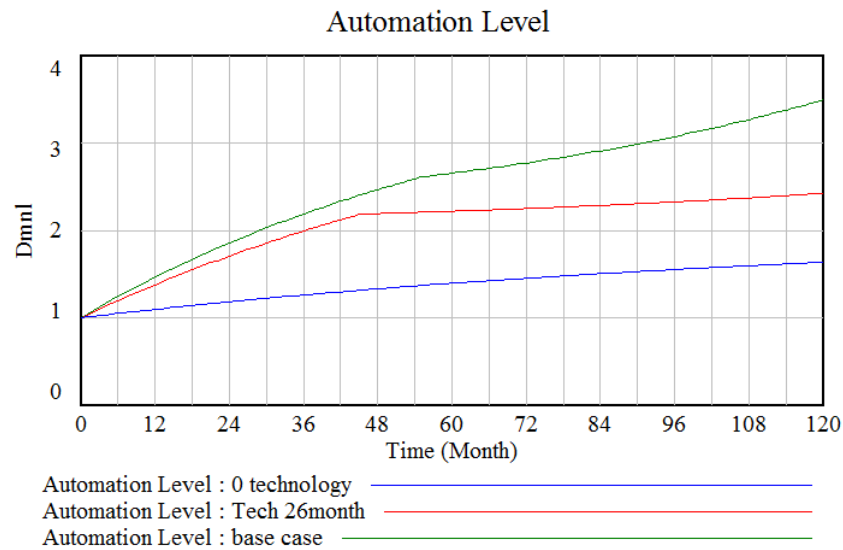


Figure 74: Automation levels of three scenarios

Figure 74 showed these three scenarios when technology implementation is 0, 18 month and 26 months. Automation level is at the lowest level when no technology implements. However, automation level is at the highest when implementing technology every 18 month. Automation level has a range from 1 to 4.

Figure 75 showed these three scenarios when technology implementation is 0, 18 month and 26 months. Manpower cost is at the highest level when no technology implements. This makes sense because the automation level is very low when no technology is implemented. As we know, more personnel are needed when automation is lower. Automation is the replacement of manpower in some way. The model told us that manpower cost is the lowest when implementing technology every 18 months.

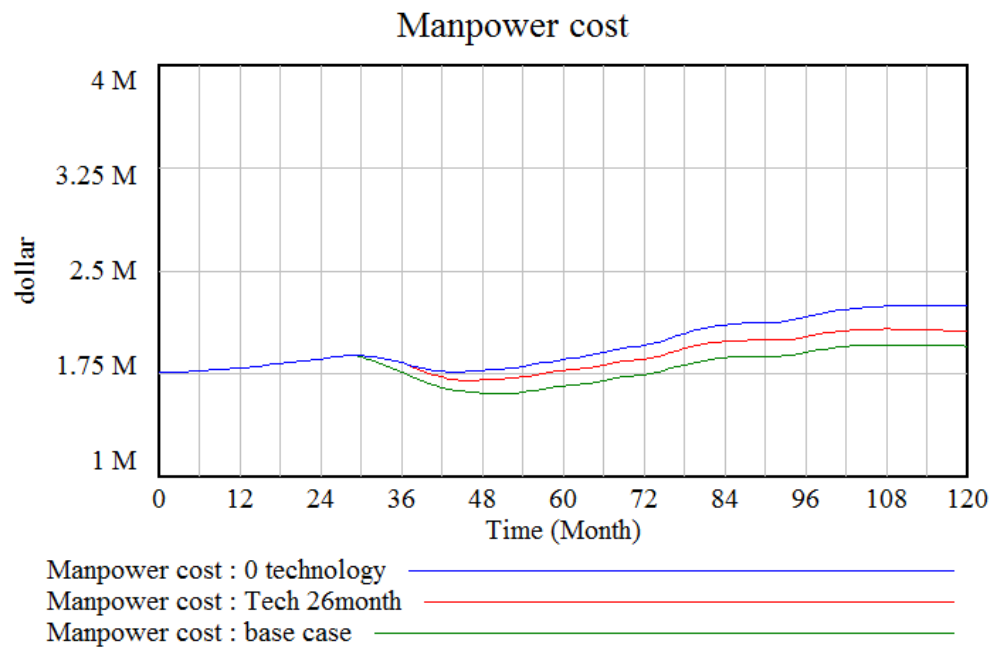


Figure 75: Manpower cost of three scenarios

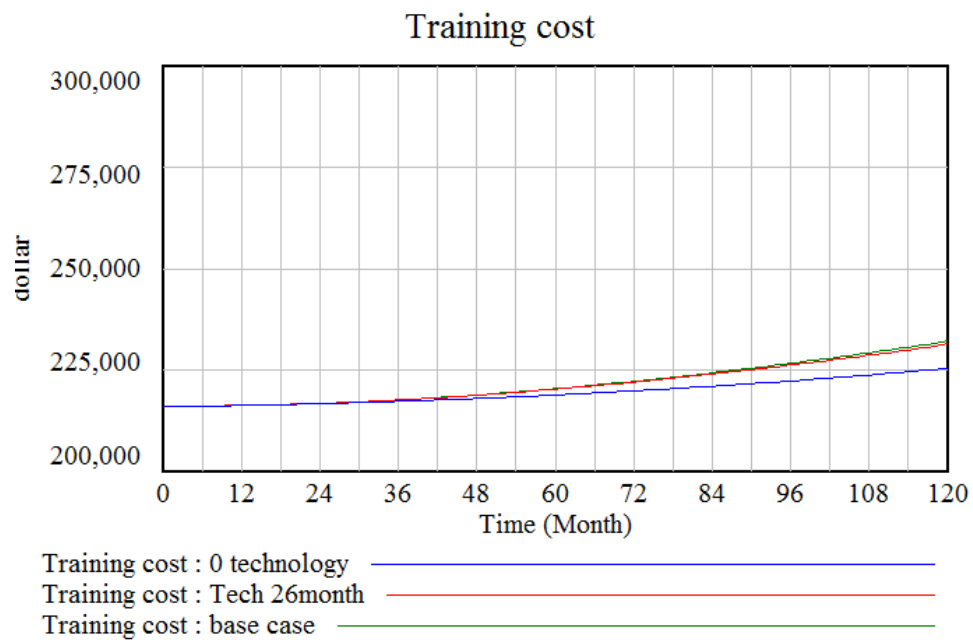


Figure 76: Training cost of three scenarios

Figure 76 showed these three scenarios when technology implementation is 0, 18 month and 26 months. It is observed that training cost is the lowest when no technology implements. This also makes sense because training requirements are very low when no new technology is implemented. Nevertheless, training cost does not change much when technology implements periods are 18 month and 26 months.

### 6.3 Model Testing

#### 6.3.1 Causal loop logic testing

Logic testing started consulting with the Navy SME and experienced modeler. The details of the causal loop diagram are listed in Appendix A.

#### 6.3.2 Integration Error test

This test is to evaluate the software's ability for consistent results for different time steps. The simulation results should not make any change for the different time steps. The following figure shows that there is not much difference when changing time steps in the model. Therefore, the model has no integration errors.

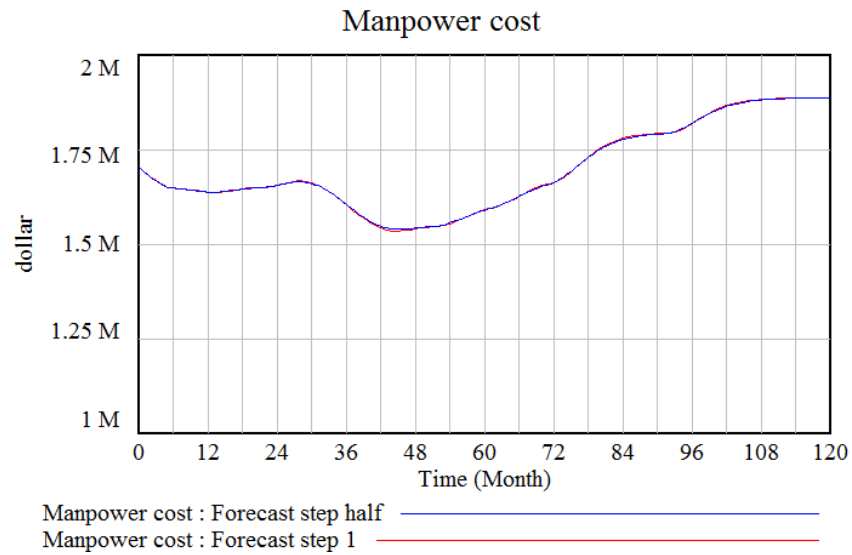


Figure 77: Simulation results for Different Time Steps

Figure 77 showed that the result when changing time steps from 1 to 0.5. As the result, the model has no integration errors.

### 6.3.3 Extreme condition test

It is necessary to robust the model by testing the model in extreme conditions. The following figure showed the Ship performance capability results with and without technology implementation. This figure reflects that ship capability increases very little without any technology implemented. This result coops with the logic of the real world.

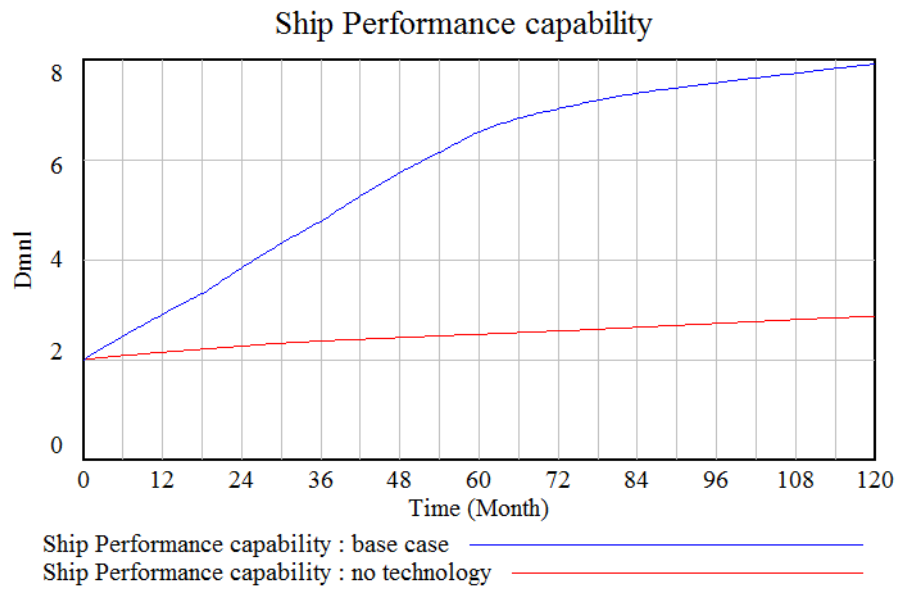


Figure 78: Extreme condition test for ship performance capability

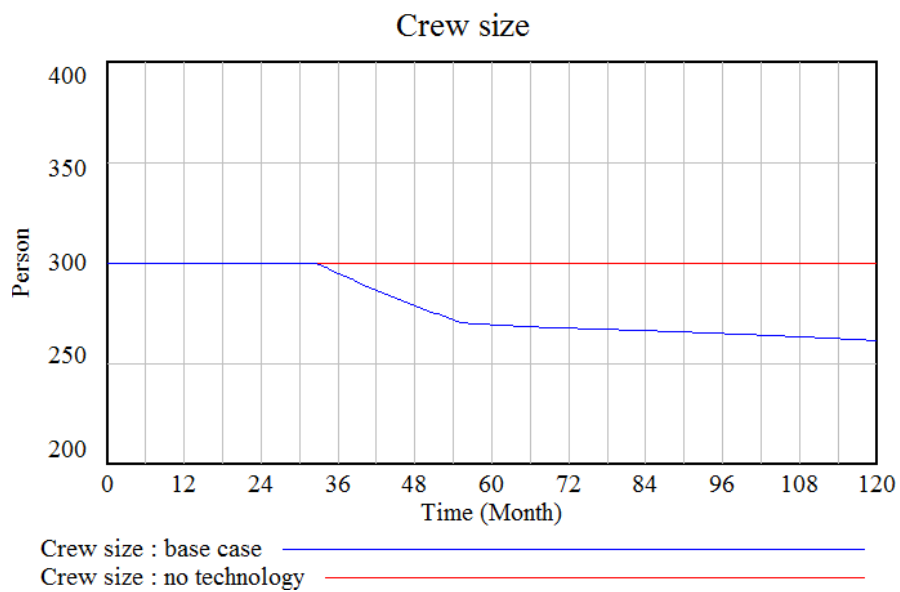


Figure 79: Extreme condition test for Crew size

Crew size will not change without implementing any new technology. However, crew size decreases as more technologies are implemented. Crew size does not change if no technology is implemented in the system. This copes with the real logic. The model result was showed in the figure 79.

#### 6.3.4 Hypothesis Test

The goal of a hypothesis test is to reproduce the behavior of manpower cost. As described before, the reference mode of manpower cost is depicted as follows in the Figure 80.

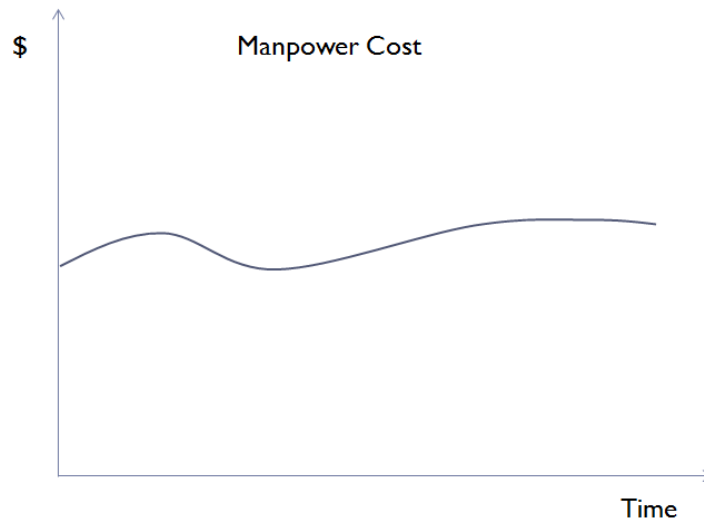


Figure 80: Reference mode

Based on the reference mode, manpower cost is forecasted to steadily increase in the next ten years. The observed output for manpower cost is shown in the Figure 81:



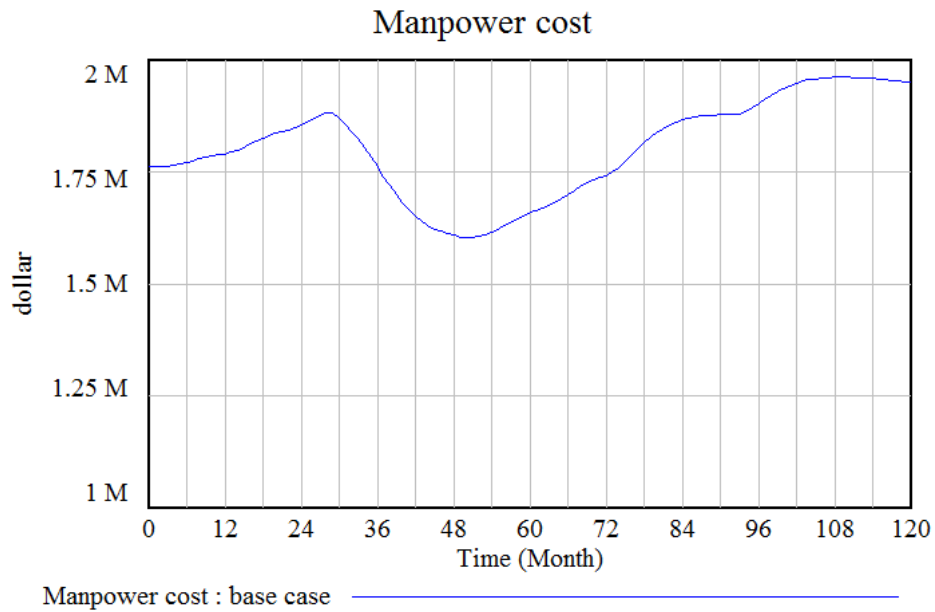


Figure 81: Observed behavior

From the observed model behaviors, the model results tested the anticipated behaviors and dynamics hypothesis result.

#### 6.4 Verification and Validation

Although Sterman (2000) says that there is no model can be verified and validated because of many assumptions made in the model.

Several methods are currently used to validate system dynamics models (Forrester, 1961). The model used historical data from the DoN to test the model. The historical timeframe selected for model testing is from 2003 to 2012.

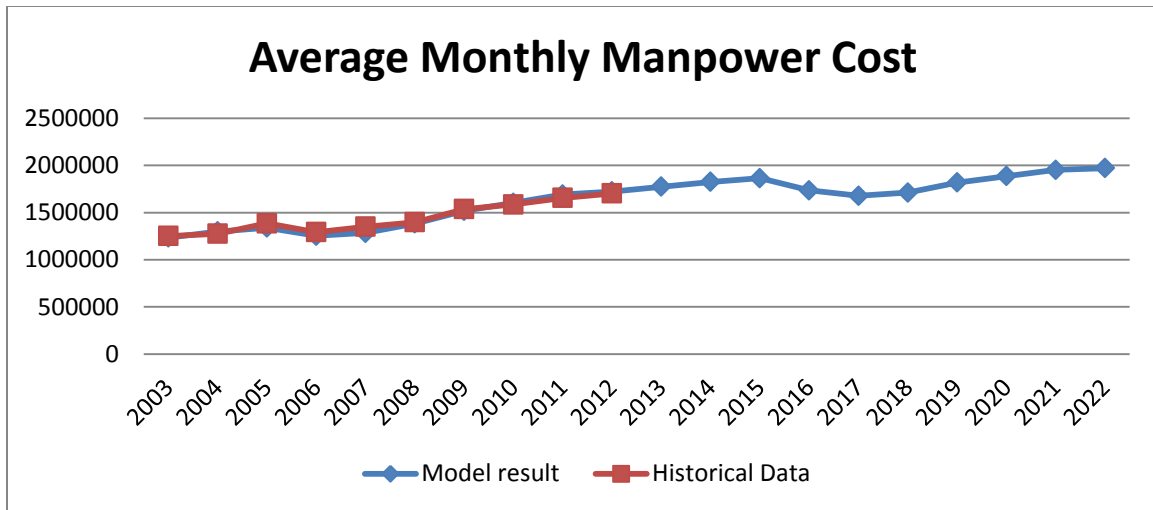


Figure 82: Average monthly manpower cost—simulation and historical data

#### 6.4.1 Manpower cost calibration

Skill based pay means paygrade levels are based on different skill levels. The higher the skill level is, the higher is the paygrade level.

Table 22 Enlisted paygrade data between DoN and model running

|                  | 2003      | 2004      | 2005      | 2006      | 2007      | 2008      | 2009      | 2010      | 2011      | 2012      |
|------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| DoN data         | 1,250,992 | 1,276,022 | 1,385,082 | 1,292,604 | 1,349,779 | 1,396,796 | 1,536,631 | 1,585,238 | 1,655,376 | 1,702,392 |
| Modeling Running | 1,234,597 | 1,298,914 | 1,340,478 | 1,253,419 | 1,284,227 | 1,383,246 | 1,517,347 | 1,603,318 | 1,691,382 | 1,723,127 |

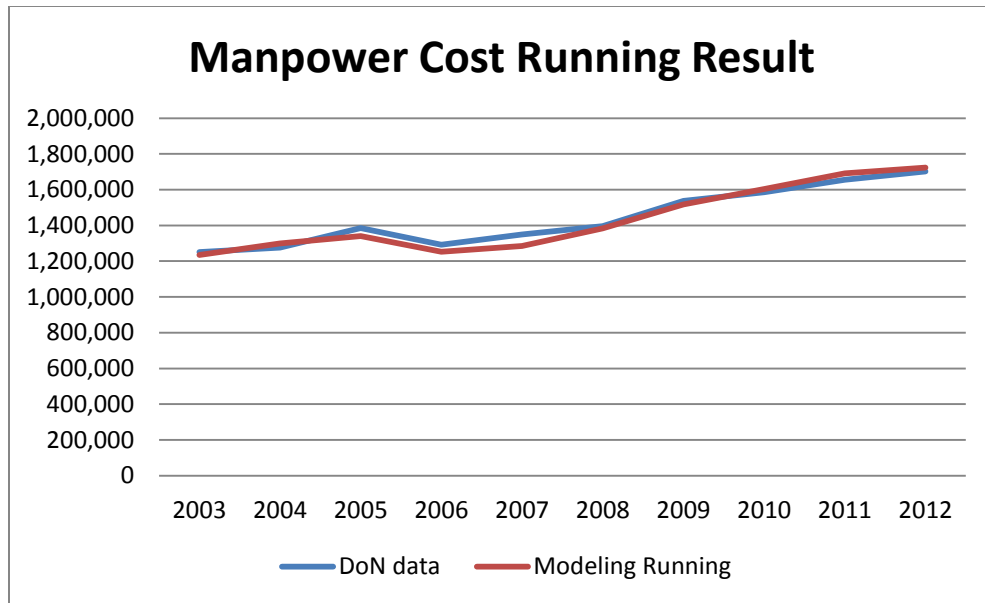


Figure 83: Calibration of manpower cost

Figure 83 showed the comparison of average monthly numbers between DoN Data and the model running result from 2003 to 2012. As mentioned previously, the model used ten years (120 months) for its time horizon. This figure showed the monthly average for 120 manpower cost data. From this figure, the model running result matches with DoN historical data. The figure also described that manpower cost steadily increasing in the next ten years. This scenario is plausible not only because it is able to generate a close replicate of the hypothetical trend, it is also able to forecast the future behavior of manpower cost. The difference between two data can be calculated by regression analysis. Table 23 showed regression results between these two data.

Table 23 Regression analysis for manpower cost

|                   |                 |
|-------------------|-----------------|
| Multiple R        | 0.988801        |
| R Square          | <b>0.977728</b> |
| Adjusted R Square | -1.25           |
| Standard Error    | 26006.41        |

“Goodness of Fit”  $R^2$  equates 0.978 which is close to 1. These two data match pretty well.

#### 6.4.2 Training Cost validating

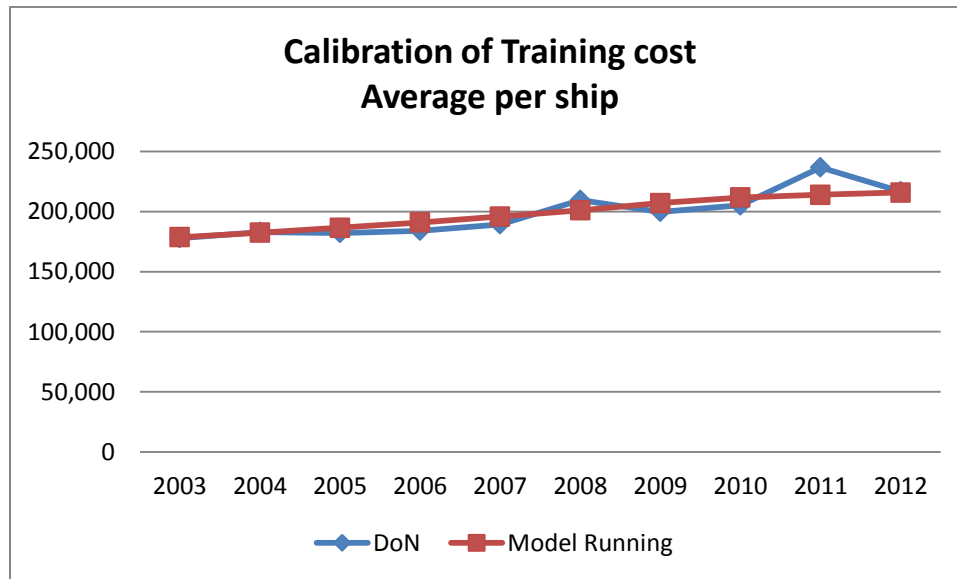


Figure 84: Ship Operation support and training cost

Figure 84 displayed the training cost onboard for ship operation support from 2003 to 2012. The blue color represented the data from the DoN, the red color represented the model running result.

The figure showed the model testing of the manpower cost from 2003 to 2012. From the figure, model running matches the data.

The difference between two data can be calculated by regression analysis. Table 24 showed regression results between these two data.

Table 24 Regression analysis for training cost

|                   |                 |
|-------------------|-----------------|
| Multiple R        | 0.880432        |
| R Square          | <b>0.775161</b> |
| Adjusted R Square | -1.25           |
| Standard Error    | 6810.031        |

“Goodness of Fit”  $R^2$  equates 0.775 which is close to 1. This number represents that two data match well.

## **CHAPTER SEVEN: CONCLUSIONs AND FUTURE STUDY**

### **Conclusion**

This research focused on tradeoff analysis and cost estimation between manpower and new technology implementation. Utilizing concepts from SDM, a causal loop diagram was built to identify major factors when implementing new technology, and then stocks and flows diagrams were built to estimate the manpower cost associated with new technology implementation. The model had been tested using data from Department of the Navy. The time horizon is ten years in this model.

As mentioned in the Chapter One, the expected research results were as follows:

- 1) Identify the major factors which impact Navy manpower cost associated with new technology implementation.
- 2) Build a system dynamic model for facilitating Navy manpower cost and training cost.
- 3) Provide information to investigate manpower cost and conduct a technology trade-off analysis so that decision makers and program managers can make better decisions.
- 4) Examine training cost for different training technologies by changing numbers of instructors.

In this research, major factors were identified that impact the Navy manpower cost when implementing new technology. Enlisted pay grades were considered for the manpower cost that included basic pay, allowance, entitlement, bonus, and retirement items for different paygrade levels. Although manpower cost components include compensations for both officers and enlisted, officer compensation is only approximately 17% of the manpower cost of a ship system.

Enlisted manpower cost accounts for 83% of the cost. This research used enlisted skill levels to estimate manpower cost. Future study needs to involve officers' cost in the model.

This research provided information to investigate manpower cost and technology trade-off associated with different technology implementation periods for decision makers and program managers. This information included skill levels, training requirement, experienced crew members, and automation levels that can be used to estimate manpower cost.

A SDM had been built for facilitating manpower cost and training cost. In addition, different scenarios of training were examined in this research. In this model, four parts of HSI were considered including manpower, personnel, training, and human factor engineering. Training provides personnel with required skill, knowledge and ability to meet requirements. Different training technologies and total numbers of instructors have different impacts on training cost, which had been examined in this research.

The modeling process is continuous and complex (Stermann, 2000). A good model needs to continuously involve with modelers and decision makers who use the model for decision making process. The strengths of this research include:

- 1) Identified major factors of manpower cost when implementing new technology.
- 2) Provided necessary information of manpower cost estimation by using system thinking for decision makers and program managers.

However, this research also has limitations since it did not include officers in the manpower cost estimation process. This caused a bias of manpower cost estimation for a ship system.

### **Significance of the study**

Significance of the study is as follows:

- 1) Major factors were identified that impact Navy manpower cost when implementing new technology.
- 2) A SDM had been built for facilitating manpower cost for the Navy.
- 3) Information had been provided to investigate manpower cost and new technology implementation trade-off and cost estimation.

### **Contributions to Literature**

I had developed a system dynamic model. This model allowed us to:

- 1) Identify manpower cost factors.
- 2) Provide necessary information for a better understanding of manpower cost drivers when implementing new technologies.
- 3) Estimate manpower cost for a Navy system.
- 4) Conduct a trade-off analysis for manpower cost and state-of-the-art technology implementation.



## **Research results**

In summary, this research coped with my expected research results. These results include that identified major factors impact Navy manpower cost associated with new technology implementation, built a system dynamic model for facilitating Navy manpower cost and training cost, provided information to investigate manpower cost and technology trade-off analysis for decision makers, and estimated training cost for different training technologies and numbers of instructors. This research also can be applied to industrial applications such as health care, Nuclear power plant, and aviation company associated with manpower cost when implementing new technology.

This research specified manpower cost by sailors' skill categories, grade, and cost element. Among these categories, skill levels can be expressed by different grade and compensation for Navy enlisted sailors. As new technologies are implemented into today's Navy ship systems, the Navy must develop different manpower requirements for specifying manpower drivers and cost. One of the major goals of this research is to assist Navy decision makers and program managers when considering the impacts of technology selection on manpower cost. Additionally, this research provides them with a better understanding of the hidden costs associated with new technology adoption.

## **Future study**

The modeling process is by its very nature always a work in progress. Future studies should work closely with the relevant Subject Matter Experts (SME) to find a better solution for the

model application areas so that the model can be improved overall. The following list is the areas recommended for future study:

1. This research used Navy public domain budget data from 2003 to 2012 for the model validation and testing, which is not ideal. The reason is that the Navy data specifies whole ship systems and therefore is not a good fit for a specific type of system. In a future study, it is recommended that a specific type of ship data be used to validate the model. Ultimately the goal for this model will be to generate generic manpower costs for any ship system associated with a new technology implementation. Therefore, using more specific data is very important for the long term validation of the model. Recommended sources would include data from the Naval Visibility and Management of Operating and Support Costs (VAMSOC).
2. Future study should include the number of officers in the model. In this research, only numbers of enlisted sailors were considered. Therefore, future study should consider officers to make the model more realistic.
3. Future study should also consider different grade levels of sailors, which will provide more details of the sailors' skill levels for decision makers. In this model, sailors' skill levels were divided into three different levels. Future study should consider adding more detail.
4. Although this study covered training, future study should expand on the training domain. Training has changed gradually from Instructor-based Training to Computer Based Training (CBT) since 2003 in the Navy. Future studies should compare different scenarios between Instructor-based training and CBT onboard and the overall effects to manpower.

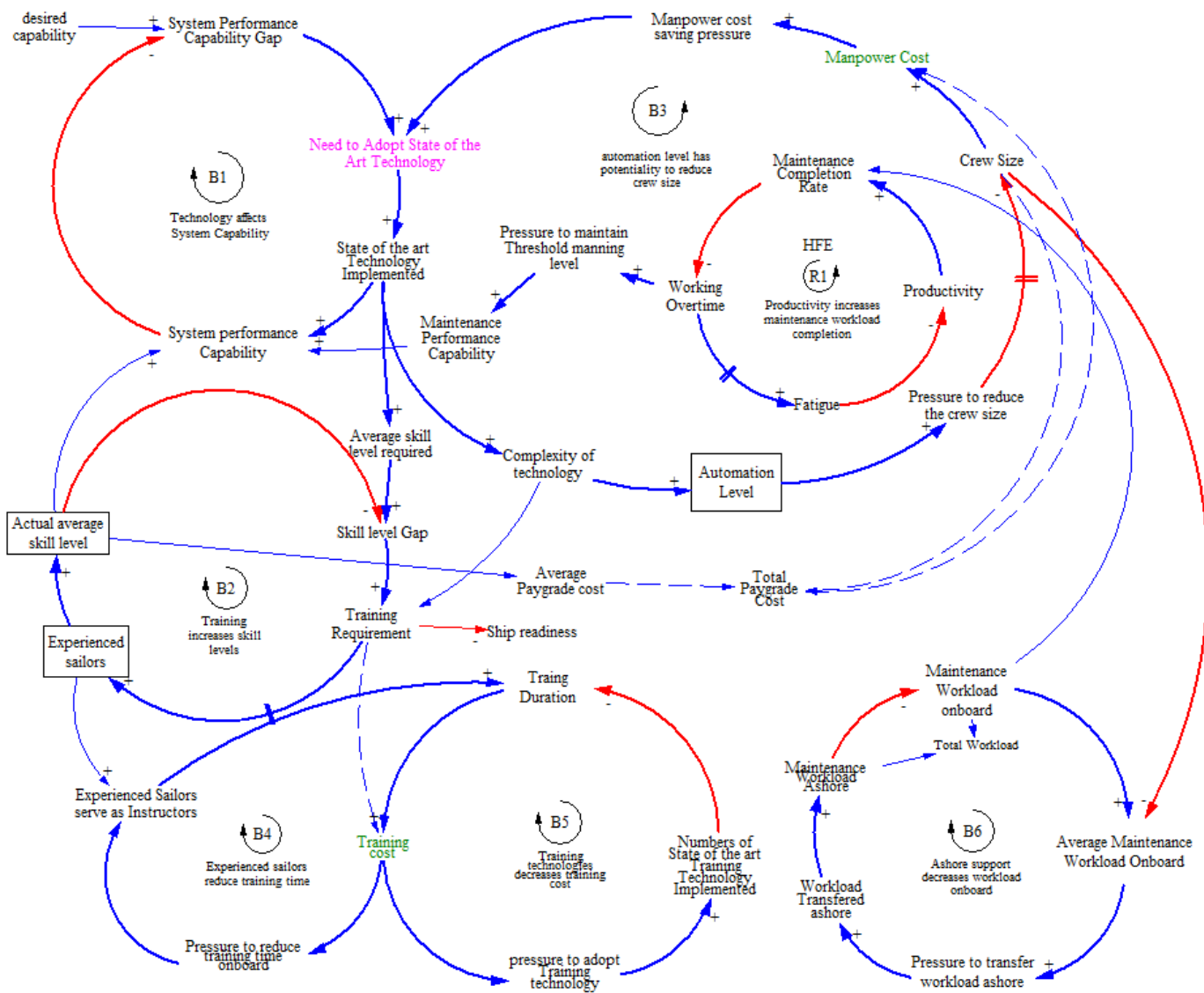
5. Additional studies should also consider maintenance workload effects. For example, workload transfer in the model show how the system capability can be affected by the amount of workload transferred to the shore. This is also critical for manpower requirements since maintenance workload is one factor of determining crew size. Therefore, it is important to determine how much workloads can be transferred to the shore in order to minimize crew size onboard and not affect ship performance.
6. In this research it was assumed that new technology was implemented for every 18 months. Future research should examine actual implementation timelines for technologies. It is reasonable that some technologies might be adoptable faster than other.
7. Lastly, in this research, the level of complexity, automation, and technology implementation periods for technology were considered in the model. Future study should combine other variables for technology consideration such as reliability, maturity, compatibility, and affordability.

**APPENDIX A: SAMPLE PUBLIC DOMAIN DATA FROM  
DEPARTMENT OF THE NAVY**

Department of Defense  
FY 2012 President's Budget  
Exhibit O-1  
Total Obligational Authority  
(Dollars in Thousands)

|   | FY 2010    | FY 2011    | FY 2012    |
|---|------------|------------|------------|
|   | -----      | -----      | -----      |
| 1804N Operation & Maintenance, Navy                           |            |            |            |
| TOTAL, BA 01: Operating Forces                                | 34,237,938 | 29,544,424 | 32,164,377 |
| TOTAL, BA 02: Mobilization                                    | 680,587    | 706,664    | 801,962    |
| TOTAL, BA 03: Training and Recruiting                         | 3,203,926  | 3,267,667  | 1,810,041  |
| TOTAL, BA 04: Admin & Srwd Activities                         | 5,007,102  | 4,615,553  | 4,588,308  |
| TOTAL, BA 20: Undistributed                                   |            | 4,340,707  |            |
| Total Operation & Maintenance, Navy                           | 43,129,553 | 42,475,015 | 39,364,688 |
| Details:  |            |            |            |
| Budget Activity 01: Operating Forces                          |            |            |            |
| Air Operations  |            |            |            |
| 1804N 010 1A1A Mission And Other Flight Operations            | 4,982,715  | 4,429,832  | 4,762,887  |
| 1804N 020 1A2A Fleet Air Training                             | 125,395    | 81,345     | 1,771,644  |
| 1804N 030 1A3A Aviation Technical Data & Engineering Services | 55,230     | 38,932     | 46,321     |
| 1804N 040 1A4A Air Operations And Safety Support              | 136,777    | 100,485    | 104,751    |
| 1804N 050 1A4N Air Systems Support                            | 513,112    | 355,520    | 431,576    |
| 1804N 060 1A5A Aircraft Depot Maintenance                     | 1,293,148  | 1,221,410  | 1,030,303  |
| 1804N 070 1A6A Aircraft Depot Operations Support              | 35,036     | 27,448     | 37,403     |
| 1804N 080 1A9A Aviation Logistics                             |            |            | 238,007    |
| Total Air Operations  | 7,141,413  | 6,254,972  | 8,422,892  |
| Ship Operations   |            |            |            |
| 1804N 090 1B1B Mission And Other Ship Operations              | 4,550,975  | 3,696,913  | 3,820,186  |
| 1804N 100 1B2B Ship Operations Support & Training             | 717,586    | 728,983    | 734,866    |
| 1804N 110 1B4B Ship Depot Maintenance                         | 6,265,286  | 4,761,670  | 4,972,609  |
| 1804N 120 1B5B Ship Depot Operations Support                  | 1,180,711  | 1,344,844  | 1,304,271  |
| Total Ship Operations   | 12,714,558 | 10,532,410 | 10,831,932 |
| Combat Operations/Support                                     |            |            |            |
| 1804N 130 1C1C Combat Communications                          | 695,359    | 615,069    | 583,659    |
| 1804N 140 1C2C Electronic Warfare                             | 79,898     | 89,340     | 97,011     |
| 1804N 150 1C3C Space Systems And Surveillance                 | 201,871    | 177,397    | 162,303    |
| 1804N 160 1C4C Warfare Tactics                                | 474,110    | 416,068    | 423,187    |
| 1804N 170 1C5C Operational Meteorology And Oceanography       | 343,674    | 316,525    | 320,141    |
| 1804N 180 1C6C Combat Support Forces                          | 2,474,781  | 1,083,618  | 1,076,478  |
| 1804N 190 1C7C Equipment Maintenance                          | 182,326    | 165,985    | 187,037    |
| 1804N 200 1C8C Depot Operations Support                       | 4,575      | 2,836      | 4,352      |
| 1804N 210 1CCH Combatant Commanders Core Operations           | 190,112    | 208,250    | 103,830    |
| 1804N 220 1CCM Combatant Commanders Direct Mission Support    | 283,736    | 274,071    | 180,800    |
| Total Combat Operations/Support                               | 4,930,442  | 3,349,159  | 3,138,798  |

## **APPENDIX B: CAUSAL LOOPS DIAGRAM**



## **APPENDIX C: STOCKS AND FLOWS EQUATIONS**



(01) Actual Average Skill Level= INTEG (Increasing skill level, 5)

Units: Dmnl

The actual skill level for the experienced sailors

(02) Advanced Technology on Complexity (

$[(0,0)-(1,10)],(0.03976,2.67544),(0.2,5.78947),(0.4,7.58772),(0.5,8.20175),$   
 $(0.6,9.21053),(0.7,9.51754),(0.8,10))$

Units: Dmnl

The current status of technology implementation

(03) Ashore Workload decreasing=

Maintenance workload Ashore/Time to complete 2

Units: manhour/Month

(04) Attrition= Attrition rate

Units: Person/Month

(05) Attrition rate= 0.1

Units: Person/Month

Experience sailor attrition rate per month

(06) Automation Level= INTEG (Increasing Automation level, 1)

Units: Dmnl

(07) Average Maintenance Workload onboard=  $30 \times (\text{Maintenance workload Onboard/Crew size})$

Units: manhour/Person

Average amount of works need to do by one sailor in one hour onboard.

(08) Average skill level req= INTEG (increasing 1, 15)

It is determined by Technology implementation rate on skill level requirement and Normal skill level changing. Normal skill level changes by self-learning and organizational learning.

(09) Capability increase fraction=

0.005

Units: Dmnl/Month

(10) Change in system capability=

$\text{capability increase fraction} \times \text{Ship capability Performance Gap} \times \text{State of the art Technology Implemented} \times \text{effect of tech numbers}(\text{Technologies Implemented})$

Units: Dmnl/Month

(11) Complexity of Technology= EXP (State of the art Technology Implemented)

Units: Dmnl

How complex of the state-of-the-art technology----complexity between state-of-the-art technology compared with the current technology

(12) Cost increasing=

$0.1 \times \text{Training requirement} \times (\text{Training cost/Training duration})$

Units: dollar/Month

It varies by Training requirement and time to train all the trainees.

(13) Crew size=

Min(Effect of Automation Level on Crew Size(Automation Level), (E5 to E7+  
E2 to E4+E8 and E9))

Units: Person

The maximum number between automation level on crew size and total Experienced Sailors and Inexperienced Sailors

(14) Desired capability= 10

Units: Dmnl

Desired ship capability from policy makers

(15) E2 to E4= INTEG (hiring-Promotion1, 190)

Units: Person

Numbers of Inexperienced sailors

(16) E5 to E7= INTEG (Promotion1-Promotion 2, 100)

Units: Person

Sailors have required experience.

(17) E8 and E9= INTEG (Promotion 2-attrition, 10)

Units: Person

(18) Effect of Automation Level on Crew Size (

[(0,0)-(4,300)],(0,300),(0.5,300),(1,300),(1.5,300),(2,300),(2.5,270),(3,  
265), (3.5,260),(4,250))

Units: Person

Higher automation is, less numbers of crew size are

- (19) effect of Experienced sailors on Skill level(

$[(120,0)-(145,1)],(120,0.1),(125,0.2),(130,0.35),(140,0.4),(145,0.5))$

Units: Dmnl/Person/Month

Experienced sailors on skill levels

- (20) Fatigue level on productivity (

$[(0.1,0.1)-(4.0,1.0)],(0,1),(1.03529,0.932384),(2,0.854093),(3,0.7),(3.5,0.6),(4,0.5))$

Units: Dmnl

Lookup table

- (21) Pressure on workload transferred (

$[(0,0)-(10,10)],(0.117647,0.355872),(1.34118,1.17438),(2.82353,1.88612),(3.64706,2.34875),(5.03529,3.52313),(5.43529,5.48043),(6.11765,7.43772),(6.94118,8.11388),(7.81176,8.71886),(9,9),(10,9))$

Units: Dmnl

- (22) effect of tech numbers(

$[(0,0)-(12,10)],(0,2),(1,2),(5,5),(8,8),(10,10),(12,10))$

Units: Dmnl

- (23) Effect of Technology implementation on Skill level required=

Effect of Technology implementation on Skill level Table (State of the art Technology Implemented

)

Units: Dmnl

The effect of the Technology implementation rate on Sailors' skill level requirement

(24) Effect of Technology implementation on Skill level Table (

[(0.1,0.1)-(1.0,1.5)],(0.1,0.5),(0.2,0.6),(0.4,0.8),(0.6,1),(0.9,1.1),(0.95,1.2),  
(1.0,1.5))

Units: Dmnl

How technology implementation rate affects on skill level

(25) effect of time on fatigue = WITH LOOKUP (Work overtime fraction,

([(0.1,0.1)-(3,2)],(0.1,0.1),(0.434251,0.0964912),(0.856269,0.280702),(1,0.6),(1.33333  
,0.837719),(1.54128,0.951754),(2,1),(3,1.5) ))

(26) effect of workload on pressure(

[(0,0)-(150,10)],(0,0),(40,3),(50,5),(60,6),(80,7),(100,8),(149.294,10))

Units: Dmnl

(27) ES for time decreasing = 1

Units: hour/Month

[(170,0)-(300,40)],(170,0),(200,10),(210,20),(220,30),(230,35),(2  
40,35),(280,35) One experienced sailor can decrease one hour.

(28) Experienced Sailors serving as Instructors=

Min ((E5 to E7+E8 and E9), E5 to E7\*Pressure to reduce training time onboard

)

Units: Person

How many Experienced Sailors serves as training instructors

(29) Fatigue Level= INTEG (Getting fatigue, 1)

Units: Dmnl

Levels change from 1 to 10. 1 is the minimum and 10 is the maximum fatigue levels

(30) FINAL TIME = 120

(31) fraction= 0.1

(32) Fraction of Ashore to Onboard=

Maintenance workload Ashore/Maintenance workload Onboard

Units: Dmnl

The ration between Ashore maintenance and onboard maintenance.

(33) Getting fatigue=

Fraction \*effect of time on fatigue\*IF THEN ELSE(effect of time on fatigue

>1, ABS (New Fatigue level)/Time to get fatigue

, ABS (Initial Fatigue level

+Fatigue Level)/Time to get fatigue)

Units: Dmnl/Month

(34) Implementation rate=

$$1*(\text{PULSE}(18, 1)+\text{PULSE}(36, 1)+\text{PULSE}(54, 1)+\text{PULSE}(72, 1)+\text{PULSE}(90,1)+\text{PULSE}(108,1))$$

Units: Technology/Month

(35) Implemented time= 9

Units: Month

Time to implement of a new training technology

(36) increasing 1= 0.1\*Effect of Technology implementation on Skill level required

(37) Increasing Automation level= 0.5\*ABS (indicated level-Automation Level)/Time to increase

Units: Dmnl/Month

Comparison of indicated Automation level and actual automation level according with the time

(38) Increasing skill level=

$$0.1*\text{effect of Experienced sailors on Skill level (E5 to E7+E8 and E9)}$$

Units: Dmnl/Month

The increasing skill level rate for the total sailors

(39) indicated Experienced sailors= 130

Units: Person

Desired numbers of experienced sailors

(40) indicated level=

IF THEN ELSE (Complexity of Technology < 2.5 : AND: Complexity of Technology > 0, Initial Level , New Automation level  
)

Units: Dmnl

(41) Indicated Training Technology Implemented=

IF THEN ELSE (Pressure to adopt Training technology < 1.2 : AND : Pressure to adopt Training technology  
> 0, Initial Training Tech  
, New Training Tech)

Units: Technology

(42) Initial Fatigue level= 1

Units: Dmnl

Initial level of Fatigue

(43) Initial Level= 2

(44) INITIAL TIME = 0

(45) Initial Training Tech= 2

Units: Technology

Initial level of Training technology

(46) Maintenance workload Ashore= INTEG (



Transferring-Ashore Workload decreasing,

0.1)

Units: manhour

here we are talking about Intermediate Maintenance.

(47) Maintenance workload Onboard= INTEG (

Onboard Workload increase-Onboard Workload Decrease,

100)

Units: manhour

It represents that workload performed onboard to maintain ship capability. It changes by Workload Completion rate deducts Workload increasing

(48) Manpower budget=

1.2e+006

Units: dollar

Money be distributed for the manpower cost in one ship PER MONTH

(49) Manpower cost= average pay for enlisted\*Crew size

Units: dollar

Manpower cost consists of compensation cost per month for all enlisted.

(50) Manpower Cost Saving Pressure=

Manpower cost/Manpower budget

Units: Dmnl

Varies by actual manpower cost and budget from government. the

higher budget the lower pressure

(51) Need to Adopt State of the art Technology = WITH LOOKUP (  
 Manpower Cost Saving Pressure\*Ship capability Performance Gap,  

$$[(0,0)-(12,1)],(0,0),(2,0.2),(4,0.4),(5.65749,0.77193),(8.10398,0.899123),$$

$$(10,0.91),(11,0.95),(12,1) )$$

Units: Dmnl

Changing by cost saving pressure and system capability performance gap.

(52) New Automation level= 4

(53) New Fatigue level= 5

Units: Dmnl

Highest fatigue level

(54) New Training Tech= 5

Units: Technology

Higher level of the Training technology be implemented

(55) Normal completion rate= 50

Units: manhour/Month

Normal completion rate without any interruption

(56) Numbers of State of the art training Technology Implemented= INTEG (

Training technology numbers changing,

2)

Units: Technology

Numbers of new training technology be implemented into the system

(57) Onboard Workload Decrease=

Time to complete  $\text{Min (ZIDZ( (Maintenance workload Onboard-Maintenance workload Ashore) ,$

$\text{), Crew size*Productivity)}$

Units: manhour/Month

Minimum number to decrease onboard workload between remains of

Workloads after transferring to ashore and crew's finishing rate

(58) Onboard Workload increase=

$\text{MAINTENANCE REQUIRED*2}$

Units: manhour/Month

Workload increases according to Maintenance requiement

(59) One tech decreases time= 2

Units: hour/Month

How much one training technology can decrease training time per sailor per month

(60) Pressure to adopt Training technology=

$\text{Training cost effect on technology adoption (Training cost)}$

Units: Dmnl

Cost pressure on adopting training technology

(61) Pressure to reduce training time onboard=

$\text{Training cost/Threshold of training cost}$

Units: Dmnl

Pressure increases when training time onboard increases

(62) Pressure to transfer workload ashore=

Fatigue Level\*effect of workload on pressure (Average Maintenance Workload  
onboard

)

Units: Dmnl

Pressure increases by increased average maintenance workload

(63) Productivity=

Effect of fatigue level on productivity (Fatigue Level)

Units: manhour/Person/Month

The effect of the fatigue level on sailors' productivity

(64) Promotion 2=

E8 and E9/time to promote2

Units: Person/Month

(65) Promotion1=

0.7\*Training requirement\*((indicated Experienced sailors-E5 to E7)/time to  
promote1

)

Units: Person/Month

Changing by the difference between Desired Experience number and

actual Experience Sailors times Training requirement 0.6\*ABS(

Training requirement\*(Desired Experienced sailors-E5 to E7)/time

to promote1 )

(66) SAVEPER =

TIME STEP

(67) Ship capability Performance Gap=

Desired capability-Ship Performance capability

Units: Dmnl

Gap between desired ship capability and actual ship capability

(68) Ship Performance capability= INTEG (change in system capability, 2)

Units: Dmnl

Ship performance capability increases by technology and skill levels

(69) Skill Level Gap=

IF THEN ELSE ( (Average skill level required -Actual average skill level)>0 ,  
Average skill level req

-Actual Average Skill Level

, 0)

Units: Dmnl

The gap between required skill level and the actual skill level

(70) standard training time= training time per sailor

Units: hour/Month

7 hours per week for one sailor. Therefore standard time per month is 28

- (71) State of the art Technology Implemented = WITH LOOKUP ( Need to Adopt State of the art Technology,  

$$[(0.1,0.1)-(1,1)],(0.1,0.1),(0.195719,0.109649),(0.409786,0.236842),(0.501529,0.504386), (0.614679,0.894737),(0.764526,0.973684),(1,1) )$$
  
 Units: Dmnl  
 how advanced level of technologies be implemented in the system.
- (72) Technologies Implemented= INTEG (Implementation rate, 1)  
 Units: Technology  
 Numbers of technologies to be implemented
- (73) Threshold of training cost= 1.85e+006  
 Units: dollar  
 Threshold of Training cost for all trainees in one month (budget consideration)
- (74) TIME STEP = 1
- (75) Time to complete= 4  
 Units: Month  
 Average time to complete a significant workload assignment
- (76) Time to complete 2= 2.5
- (77) Time to get fatigue= 10  
 Units: hour

Number of working hours to getting fatigue

(78) Time to increase= 36

Units: Month

Actual time to increase automation level. It takes 3 years for policy makers to make the decision for increasing automation level

(79) time to promote1= 48

Units: Month

How many months are needed to acquire experienced sailors

(80) time to promote2= 120

Units: Month

How many months are needed to acquire experienced sailors

(81) Training cost= INTEG (Cost increasing, 216000)

Units: dollar

Training cost for all trainees in one month. OJT training

(82) Training cost effect on technology adoption(

[(100000,0)-(185000,2)],(100000,0.4),(170000,0.5),(172000,0.6),(177000,0.7),  
(178000,0.8),(179000,0.9),(180000,1),(185000,1.47331))

Units: Dmnl

Lookup table

(83) Training duration=

Instructors (Standard training time-ES for time decreasing\*Experienced Sailors serving as

-Numbers of State of the art training Technology Implemented

\*One tech decreases time)\*E2 to E4

Units: hour/Month

Total time for ES to train all the trainees

(84) Training requirement = WITH LOOKUP (

Skill Level Gap,

[(0,0)-(30,5)],(0,0),(6.56471,1),(12.2824,2),(14.5412,3),(18.5321,4),(23.5765,4.5),(30,5) )

Units: Dmnl

Changing by Skill level Gap. The higher skill level gap is, the higher Training is required.

(85) Training technology numbers changing=

(Indicated Training Technology Implemented-Numbers of State of the art training Technology Implemented

)/Implemented time

Units: Technology/Month

It changes by indicated training technologies and actual numbers

of training technologies (Indicated Training Technology

Implemented-Numbers of State of the art training Technology

Implemented)/Implemented time

(86) training time per sailor= 28



Units: hour/Month

Training time per sailor per month. Data from Navy manpower requirement. 10% for training.

(87) Transferring=

Workload transfer to ashore\*10

Units: manhour/Month

(88) Work overtime fraction=

ZIDZ(Onboard Workload Decrease, Normal completion rate )

Units: Dmnl

Percentage between normal completion rate and actual workload completion rate

(89) Workload transfer to ashore=

effect of pressure on workload transferred(Pressure to transfer workload ashore )

Units: manhour/Month

Workloads need to transfer to ashore in order to decrease onboard burdens

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